Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
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THERMAL AND HYDRAULIC BEHAVIOR OF CANDU CORES UNDER SEVERE ACCIDENT CONDITIONS

by

J.T. Rogers
Carleton University

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ABSTRACT

This report describes work performed for the Atomic Energy Control Board on a) Formation and rewetting of dry patches on CANDU reactor calandria tubes during a Loss-of-Coolant Accident, and b) Analysis of accident sequence S11: Loss-of-Coolant Accident plus Loss-of-Emergency Core Cooling plus loss of moderator cooling system.

For part (a), it is concluded that any dry patches which form on calandria tubes as a result of local heating to the critical heat flux will rewet in a short time (10 to 30 seconds for a Bruce-type reactor, 90 seconds for a Douglas Point-type reactor), with negligible effects on fuel sheath and maximum pressure tube temperatures. Pressure tube integrity is not predicted to be threatened.

For part (b), preliminary analysis of the S11 accident sequence is presented. The complete analysis follows in the final report on the effects of severe accidents on CANDU cores.

RÉSUMÉ

Le présent rapport décrit le travail effectué pour la Commission de contrôle de l'énergie atomique en ce qui concerne a) la formation et le remouillage de points secs sur les tubes de la cuve du réacteur CANDU au cours d'une perte de caloporteur, et b) l'analyse de la séquence d'accidents S11 : perte de caloporteur, perte du refroidissement d'urgence du coeur et perte du système de refroidissement du modérateur.

Eu égard à l'article a), l'étude a permis de conclure que le remouillage de tout point sec qui se forme sur les tubes de la cuve à la suite d'un chauffage ponctuel atteignant le flux thermique critique, s'effectuera rapidement (en 10 à 30 secondes dans le cas d'un réacteur de type Bruce, en 90 secondes dans le cas d'un réacteur du genre Douglas Point), et que les conséquences sur les températures de la gaine du combustible et sur les températures maximales des tubes de force seront de peu d'importance. Il n'y aurait aucune atteinte à l'intégrité des tubes de force.

En ce qui concerne l'article b), le présent rapport esquisse une analyse préliminaire de la séquence d'accidents S11. L'analyse complète figure dans le rapport final relatif aux conséquences des accidents graves sur le coeur des réacteurs CANDU.

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Nomenclature

CHF - critical heat flux

CT - calandria tube

F1 to F4 - fuel ring number

FEPR - maximum fuel element power rating in bundle, W/cm.

PT - pressure tube

$S1_i$ or $S1_o$ to $S3_i$ or $S3_o$ - sheath number

T_Q - quenching temperature, ^oC

ΔT_{minFB} - minimum film boiling temperature, ^oC

ΔT_{SUB} - liquid sub-cooling, ^oC

θ - angular position from bottom of calandria tube, degrees

Subscripts

i - inside

o - outside

INTRODUCTION

This report describes work undertaken for the Atomic Energy Control Board under contract serial number OSU80-00237 over the period August 17, 1980 to February 18, 1982, on the Thermal and Hydraulic Behavior of CANDU Cores Under Severe Accident Conditions.

Previous work for AECB related to the present work is described in references 1 and 2.

This report is divided into two sections:

1. Formation and Re-wetting of Dry Patches on Calandria Tubes During a LOCA
2. Analysis of Accident Sequence S11: LOCA - LOECC - Loss of Moderator Cooling System.

Part 1. Formation and Re-wetting of Dry Patches on Calandria Tubes During a LOCA

1.0 INTRODUCTION

In previous work related to that described here, the computer program IMPECC (3, 4, 5) was used to investigate the effects of a dry patch of fixed size located at the bottom of the calandria tube on the thermal behavior of a Bruce Reactor fuel channel following a LOCA with impaired ECC (2). The dry-patch was assumed to be caused by the occurrence of critical heat flux locally when the pressure tube sagged onto the calandria tube, even though it had been concluded from earlier studies that CHF will not occur under these conditions (3, 4). Based on several IMPECC runs with different-sized fixed dry patches, it was concluded that, for CANDU reactors in which the calandria tubes remain submerged during the accident sequence considered, a dry patch caused by local CHF on the calandria tube will initially spread but will not grow beyond a total angle of about 10° after which re-wetting of the dry patch will occur. It was also concluded that the whole process will take place quite rapidly and the maximum local calandria tube temperatures reached will not be excessive. Finally, it was concluded that calandria tube and pressure tube integrity will almost certainly be maintained. However, it was recognized that confirmation of these conclusions would have to await the development of the modified version of IMPECC which allows for dry patch spreading and shrinking.

For CANDU reactors which rely on moderator sprays for cooling of the calandria tubes following a LOCA with impaired ECI, where dry patch

formation resulting from falling film disruptions is almost certain, no definite conclusions could be drawn from the fixed-patch IMPECC runs. Again, it was recognized that conclusions would have to await the development of the modified version of IMPECC which allows for dry-patch spreading and re-wetting.

This modified version of IMPECC has now been developed and results of several runs are available. The modifications to IMPECC for this purpose and the results obtained are described in this part of the report.

2.0 MODIFICATIONS TO IMPECC

The modifications to IMPECC to permit the analysis of dry-patch spreading and re-wetting are described briefly here. A dry patch is assumed to form at a node on the calandria tube when the calculated surface temperature at that node reaches a value corresponding to that at critical heat flux on the boiling curve. The dry patch advances node-by-node as the surface temperature at the node just beyond the edge of the dry patch reaches the critical value. The specified critical heat flux is an input variable for the program, QDNB1, and may be the true critical heat flux for a submerged tube or the film disruption heat flux for a film-cooled tube. Similarly, re-wetting of a node at the edge of the dry patch is assumed to occur when the temperature of the node drops below a specified re-wetting temperature which is also an input variable for the program TLD1. The dry-patch shrinks node-by-node as the temperature of the node at the edge of the dry patch drops below the specified re-wetting temperature.

To predict the calandria tube outer-surface temperatures and heat fluxes for this case requires appropriate heat transfer coefficient correlations to be used for the various heat transfer regimes involved. The heat transfer regimes and the transition points between regimes are shown in Figure 1, as described below. For conditions below the onset of nucleate boiling, the heat transfer mechanism is that of natural convection and the correlation used is a conventional one for turbulent natural convection to water from a horizontal tube, as employed in the standard version of IMPECC (3). Beyond the onset of nucleate boiling, the program uses an equation based on the experimental data of McAdams for sub-cooled boiling of water at

low pressures, again as in the standard version of IMPECC (13). For heat transfer from the dry-patch in the film boiling regime, the modified program now uses the equation of Breen and Westwater for film boiling from horizontal tubes (6), allowing for the contribution of radiation heat transfer.*
For the transition boiling regime between the nucleate and film boiling regimes, an approximate boiling curve was established by linear interpolation between the specified critical heat flux value, and corresponding temperature, at the upper limit of the nucleate boiling curve and the specified re-wetting temperature, and corresponding heat flux, which was taken as the minimum film-boiling temperature at the lower limit of the film-boiling curve. The calculation of the appropriate heat transfer coefficient for the regime existing at any node on the outer surface of the calandria tube is done in the new sub-routine BOIL.

Since the heat flux may change significantly with a small change in surface temperature in the nucleate boiling and transition boiling regimes and since the boundary conditions at a node may change abruptly as the node dries out or re-wets, two changes have been made to IMPECC to permit the effective boiling curve to be followed accurately and to avoid mathematical instabilities. These two changes consist of the use of a greater number of nodes around the calandria tube, with a greater proportion of smaller nodes, and a sub-division of the normal time steps.

In the modified IMPECC, 70 nodes around the calandria tube, rather than 33 (5), are used with 38 nodes at the smallest node size of 0.275 degrees,

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* In the standard version of IMPECC which can handle analysis of the effects of a fixed dry patch on the calandria tube, the heat transfer rate across the dry patch from the calandria tube to the moderator is assumed to be zero.

covering a total angle of about 10.2 degrees on each side of the bottom point of the calandria tube, rather than 10 nodes of this size, covering a total angle of about 2.5 degrees. A comparison of the node sizes and distributions in the standard and modified forms of IMPECC is given in Table 1. To permit the sub-division of the time steps, in the new version of IMPECC the former sub-routine GELVB, which solved the finite-difference equations by Gaussian Elimination, is replaced by two sub-routines, CHLSKI and SUB. The use of these two sub-routines permits the already small time steps used after pressure tube contact with the calandria tube, in this case 5×10^{-5} hours (0.18 seconds), to be sub-divided further into extremely small time steps. The new input variable NSTLIN specifies the number of smaller (minor) time steps into which the existing initial (major) time step is divided. A value of NSTLIN equal to 50 has been used in the cases run so far. The use of such small time steps, 3.6×10^{-3} seconds in these cases, enables the program to compute accurately the rapidly changing conditions on the calandria tube exterior as the dry patch spreads and eventually shrinks. The sub-routines CHLSKI and SUB enable very short time steps to be used without requiring an excessive amount of computer time. The sub-routine CHLSKI uses Choleski matrix decomposition to factor the coefficient matrix into upper and lower triangular forms (7). The radiation components of the coefficients in the matrix are held constant during a major time step, that is, they do not change from one minor time step to the next. By treating the problem as linear between major time steps, the factorization of the finite-difference coefficient matrix which is very time consuming does not have to be performed at the minor time steps. This simplification, together with the sub-routine

TABLE 1

COMPARISON OF NODE SIZE DISTRIBUTION ON CALANDRIA TUBE
IN STANDARD AND MODIFIED VERSIONS OF IMPECC

Node Size, degrees	Standard IMPECC (5) Node Numbers	Standard IMPECC (5) Number of Nodes	Modified IMPECC Node Numbers	Modified IMPECC Number of Nodes
0.275	1-10	10	1-38	38
0.55	11-13	3	39-41	3
1.10	14-16	3	42-44	3
2.20	17-19	3	45-47	3
4.40	20-22	3	48-52	5
7.60			53-70	18
				70
8.80	23 & 24	2		
15.0	25-33	9		
		33		

SUB which performs the forward and backward substitution phases of the complete equation solving process, permits rapid determination of the new temperatures and surface heat fluxes for each minor time step. After all the minor time steps in one major time step are completed, the coefficients for the conductance matrix are re-calculated allowing for the current radiation contributions and the procedure is then repeated for the next major time step. The advantage of this method, as mentioned above, is that, while the re-calculation and factorization of the conductance matrix are time-consuming, the computations over the minor time steps are very fast, resulting in an overall rapid calculation procedure.

To conserve print-out time, the temperatures and heat fluxes at each node on the outer surface of the pressure tube are not printed out for each time step in the modified version of IMPECC as they are in the standard version; only the values for the outer surface of the calandria tube are printed out, as in the standard version. However, the maximum and minimum temperatures on the outside surface of the pressure tube, and their angular locations are printed for each time step.

3.0 RESULTS

Three cases have been run so far using the modified version of IMPECC, two for Bruce reactor conditions and one for the Douglas Point reactor. The results of these cases are discussed below.

3.1 Bruce Reactor

Important input conditions for the two cases run for a Bruce reactor unit are given in Table 2. Other input conditions were the same as for the Bruce standard case in which critical heat flux does not occur on the calandria tube.

The value of critical heat flux used in the two Bruce cases, 240 W/cm^2, is the predicted "steady state" critical heat flux for a submerged tube under uniform heat flux conditions with a nominal sub-cooling of 30°C (3). It is emphasized, as stated in reference 3 and elsewhere (4, 8, 9), that critical heat flux will not normally occur should a pressure tube sag onto a calandria tube in a Bruce reactor unit because of the very small area and exceedingly short time over which the calculated local heat flux exceeds the nominal CHF value, which results in insufficient energy transfer during the heat flux peaking period for CHF actually to occur. Nevertheless, for the present cases it is assumed that CHF will occur locally when the predicted heat flux reaches 240 W/cm^2.

Many variables govern the effective re-wetting temperature or the apparent quenching temperature (e.g., 10, 11). For the present conditions, the most realistic estimates of the quenching temperature can be obtained from the correlations for the minimum film boiling temperature of Bradfield (12) and of Dhir and Purohit (13).

TABLE 2

CONDITIONS FOR IMPECC RUNS FOR BRUCE WITH TRANSIENT DRY-PATCH BEHAVIOR

FEPR - 48 W/cm

PT Sags at 1000°C

Bundle Slumps at Node 10 (Outer Ring Fuel) at 1300°C

No radiation heat transfer from top of slumped bundle to upper 60° of pressure tube.

Case	1	2
Assumed CHF, W/cm^2	240	240
Assumed Quenching Temperature, °C	350	250

The minimum film boiling temperature for water at pressures close to atmospheric pressure is given by Bradfield as:

$$\Delta T_{minFB} = 195 + 6.25\ \Delta T_{SUB} \qquad (1)$$

and by Dhir and Purohit as:

$$\Delta T_{minFB} = 101 + 8\ \Delta T_{SUB} \qquad (2)$$

where all temperatures are in degrees Celsius.

For the nominal moderator sub-cooling of 30°C, these correlations predict minimum film boiling temperatures of 483°C and 442°C respectively. For zero sub-cooling, minimum film boiling temperatures of 296°C and 202°C, respectively, are predicted. Because of uncertainties in the application of the correlations to the present conditions resulting from geometric and material differences and because of uncertainties in the actual value of the local sub-cooling, the values of re-wetting temperatures used in the Bruce runs were taken as 250°C and 350°C. Even the higher of these two values should be conservative notwithstanding the uncertainties mentioned above while the lower value is very conservative.

3.1.1 Quenching temperature of 350°C

Results for the quenching temperature of 350°C, probably the more representative value, are given in Figures 2 to 7. Figure 2 gives the outer surface temperature and heat flux at the bottom of the calandria tube ($\theta = 0^{\circ}$) as a function of time just before and immediately following sagging of the pressure tube onto the calandria tube, which occurs in this case at 255.4 seconds after the initiating pipe rupture. For the assumed critical heat flux of 240 W/cm^2, the dry patch forms almost instantaneously, following

which the local surface heat flux drops rapidly to a minimum value of about 4.7 W/cm^2. A maximum temperature of about 580°C is reached on the outer surface of the calandria tube about 2.6 seconds after the pressure tube sags. After the peak temperature is reached, the calandria tube temperature drops relatively slowly until the quenching temperature of 350°C is reached about 8.6 seconds after the pressure tube sags, following which the temperature plummets to about 136°C. Upon re-wetting, the local heat flux rises rapidly to a value just below the assumed CHF value and then decreases moderately quickly.

Further information for this case is given in Figures 3 to 5 in which the temperatures and heat fluxes on the calandria tube are shown as functions of angular position for various times after the pressure tube sags onto the calandria tube. Also shown in these figures are the surface temperatures and heat fluxes on the calandria tube for essentially the same conditions for the expected case in which CHF does not occur, taken from earlier runs using the standard version of IMPECC.*

Figures 3 to 5 show the initial spreading of the dry patch and its eventual shrinkage. The maximum extent of dry patch is about 3.6 degrees on each side of the bottom of the calandria tube at about 2.5 seconds after

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* There is a slight difference between the conditions for the two sets of runs, in that the earlier results were obtained assuming a constant and uniform temperature at the outer surface of the calandria tube. The use of this boundary condition instead of the more realistic one of a variable heat transfer coefficient on the calandria tube has been shown earlier to result in no significant differences in local values of heat fluxes and pressure tube, fuel and sheath temperatures at any time (4).

the pressure tube sags onto the calandria tube. The growth and shrinkage of the dry patch is shown more clearly in Figure 6 where its maximum extent at a given time, taken as the angular position beyond which the heat flux increases rapidly as shown in Figures 3 to 5, is plotted against time.

These results show that, for the highly improbable case of CHF occurring on the calandria tube, at a local value of 240 W/cm^2, the maximum temperature reached by the calandria tube, at $\theta = 0^\circ$, would not be excessive. Relatively high calandria tube temperatures would persist for only a few seconds and cover only a small region. Therefore, we may conclude that, in the very unlikely event that CHF occurs, calandria tube integrity is almost certain to be maintained.

The negligible effect of the transient dry patch on fuel temperatures is clearly demonstrated in Table 3 where the temperatures of the fuel rings at various times after PT/CT contact are given for the case with CHF = 240 W/cm^2 and $T_Q = 350^\circ C$ and for the corresponding expected case with no CHF.* No direct information on maximum local pressure tube temperatures was obtained in this run, since the print-out of this quantity, mentioned earlier, was not incorporated in the modified IMPECC at this time. However, from results for a subsequent run with $T_Q = 250^\circ C$, it is evident that maximum pressure tube temperatures will not be changed from those predicted for the expected case with no critical heat flux by the presence of a transient dry patch.

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* The fact that the temperatures with no CHF are slightly higher than those with CHF in some cases may be attributed to the effect of the constant temperature boundary condition used in the standard case. As pointed out in reference 4, the use of this boundary condition results in slightly higher predicted temperatures than would be predicted with a variable heat transfer coefficient boundary condition.

TABLE 3

EFFECT OF CALANDRIA TUBE CHF
ON FUEL TEMPERATURES

Bruce Reactor

Assumed T_Q = 350°C

Time After PT Contact with CT, sec.	Fuel Ring	Temperatures, °C CHF = 240 W/cm²	NO CHF
0.18	F1	1339	1340
	F2	1353	1354
	F3	1369	1370
	F4	1300	1300
1.08	F1	1343	1343
	F2	1357	1358
	F3	1372	1372
	F4	1302	1302
6.83	F1	1366	1370
(7.56 - NO CHF)	F2	1382	1385
	F3	1390	1393
	F4	1313	1314

Therefore, we may also conclude that, should CHF occur with a quenching temperature of 350°C, the integrity of the pressure tube will not be jeopardized.

The comparisons of the present results with those for the corresponding expected case in which CHF does not occur on the calandria tube, as given in Figures 3 to 5, show good agreement between local heat fluxes at angular positions a few degrees beyond the edge of the dry patch. This fact helps to provide confidence in the results obtained with the modified IMPECC which allows for transient dry-patch behavior.

Additional confidence in the numerics of the modified IMPECC program is obtained by comparing the calandria tube temperatures and heat fluxes at a given time after the pressure tube sags onto the calandria tube for a previous case in which a large fixed dry patch was assumed on the calandria tube with the present case of a transient dry patch. Such a comparison is shown in Figure 7, where earlier results for a dry patch covering a total angle of 10.46°, i.e., 5.23° on each side of the bottom of the calandria tube (2), are compared to those for the present case at a time of 2.52 seconds after contact between the pressure and calandria tubes. This time was chosen since it represents the time when the transient dry-patch reaches its maximum extent, 3.6° on each side of $\theta = 0°$, which is about 1.6° less than that of the extent of the fixed dry patch. It is also very close to the time at which the heat flux at the edge of the fixed dry patch reaches its maximum value (See Figure 5 of reference 2).

Figure 7 shows that the peak heat fluxes are about the same for the two cases, occurring about one degree apart, and that the heat fluxes approach

each other closely a few degrees outside the dry patches. The peak temperatures are somewhat higher for the fixed dry patch than for the transient one as would be expected from the greater extent of the fixed dry patch as well as from the insulated boundary condition assumed to exist over it. However, beyond the edge of the fixed dry patch, the predicted temperatures are essentially the same for the two cases.

3.1.2 Quenching temperature of 250°C

Only a few results for the quenching temperature of 250°C will be presented here, because it is considered to be a very conservative value, as pointed out earlier. However, certain results at this low quenching temperature are useful to indicate trends and to provide further confidence in the predictions of the modified IMPECC code.

Figure 8 compares the calandria tube maximum temperatures, at $\theta = 0^{\circ}$, for the two quenching temperatures. As would be expected, with the lower quenching temperature, the maximum temperature reached is higher, about 650°C compared to about 580°C, and it occurs somewhat later. The calandria tube cool-down proceeds more slowly for the lower re-wetting temperature, but it is apparent from Figure 8 that the relatively more rapid cool-down which precedes actual quenching is beginning at about 17.6 seconds after the pressure tube sags. Unfortunately, the run was stopped before actual quenching was observed. However, it is apparent from the curves of Figure 8 that quenching would have occurred within a few seconds of the last time step used. Obviously, the time for complete re-wetting of the dry patch is considerably longer for the lower quenching temperature than for the higher one, but the re-wetting still occurs within a very short period, of the order of 25 to 30

seconds after the pressure tube sags onto the calandria tube. This conclusion is reinforced by the evidence of Figure 9 which shows the growth and shrinkage of the dry patch for the lower quenching temperature. It is evident from Figure 9 that the dry patch begins to shrink about 8 seconds after the pressure tube sags onto the calandria tube.

The effects of the lower quenching temperature on fuel temperatures and pressure tube maximum temperatures are shown in Table 4. It can be seen that, for the times given in the table, there are absolutely no differences between the fuel temperatures for the two values of T_Q. Unfortunately, comparisons at longer times after pressure tube sagging are not available since the run for $T_Q = 350^{\circ}C$ was terminated shortly after 10 seconds. While no differences exist for the times shown, some differences may occur at longer times because of the relatively large time constant of the fuel bundle.

3.1.3 Evaluation of results for Bruce reactor

The foregoing results show that, in the highly improbable event of CHF occurring on the calandria tube following pressure tube sagging, the maximum calandria tube temperatures reached would be quite moderate and the very small dry-patch formed by CHF would soon re-wet. There would be no threat to the integrity of the calandria tube. There would be essentially no effects on the fuel, sheath, and local maximum pressure tube temperatures. These results confirm, in all respects, the tentative conclusions reached in reference 2, based on results for fixed dry patches of different sizes, on the behavior of transient dry patches and their effects.

TABLE 4

EFFECT OF QUENCHING TEMPERATURE ON FUEL AND MAXIMUM PRESSURE TUBE TEMPERATURES

Bruce Reactor

Assumed CHF = 240 W/cm^2

Time After PT Contact with CT, sec.	Component	Temperatures, °C T_Q = 250°C	T_Q = 350°C	NO CHF
0.18	F1	1339	1339	1340
	F2	1353	1353	1354
	F3	1369	1369	1370
	F4	1300	1300	1300
	PT (max.)	985	-	985
6.83 (7.56 - NO CHF)	F1	1366	1366	1370
	F2	1382	1382	1385
	F3	1390	1390	1393
	F4	1313	1313	1314
	PT (max.)	1012	-	1027
10.07	F1	1381	1381	1380*
	F2	1397	1397	1395
	F3	1402	1402	1401
	F4	1320	1320	1319
	PT (max.)	1027	-	1030
17.63	F1	1410	-	1412*
	F2	1426	-	1423
	F3	1424	-	1423
	F4	1334	-	1332
	PT (max.)	1058	-	1038

* Interpolated

It is important to recognize that the two quenching temperatures used in the analyses are probably conservative, particularly the lower value of 250°C.

There is another element of conservation in the analysis. As mentioned previously, in section 2.0, heat transfer from the dry patch in the film boiling regime is calculated using the Breen and Westwater equation for film boiling from horizontal tubes (6). This equation is based on experiments using a saturated coolant and so is valid only for saturated conditions. It has been known for some time that sub-cooling of the liquid increases film boiling heat transfer coefficients significantly above those for a saturated liquid (14). Recently, Dhir and Purohit developed a correlation for sub-cooled film boiling on small spheres under natural convection conditions (13). Gillespie modified the correlation coefficients of the correlation of Dhir and Purohit, based on experiments on a 10 cm. diameter cylinder, to produce a correlation that can be used to predict natural-convection sub-cooled film-boiling heat transfer coefficients on calandria tubes (15). The significant effect of sub-cooling of the liquid on natural-convection film-boiling heat transfer coefficients is shown in Table 5, where a sub-cooling of 30°C is seen to increase the film boiling heat transfer coefficient by a factor of about 5.5 at a calandria tube surface temperature of 300°C and by a factor of about 3.0 at a calandria tube surface temperature of 600°C.*

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* Note that there is good agreement between the predictions of the two correlations for saturated liquid conditions.

TABLE 5

COMPARISON OF FILM BOILING HEAT TRANSFER COEFFICIENTS

EFFECT OF SUB-COOLING

Correlation	Heat Transfer Coefficients, W/m^2K Breen & Westwater (6)	Gillespie (15)
$\Delta T_{SUB} = 0^{\circ}C$ (saturated liquid)		
Calandria Tube Surface Temperature, $^{\circ}C$		
300	193.6	205.2
600	160.8	172.8
$\Delta T_{SUB} = 30^{\circ}C$		
Calandria Tube Surface Temperature, $^{\circ}C$		
300	-	1122.3
600	-	530.1

Obviously, had the correlation of Gillespie been used in the modified IMPECC program rather than that of Breen and Westwater, the maximum predicted temperatures of the calandria tube reached during the existence of the transient dry patch would have been significantly lower than those reported here and the re-wetting times would have been shorter.

The correlation of Gillespie will be incorporated into the modified IMPECC program so that future analyses of dry-patch behavior can be done on a more realistic basis.

3.2 Douglas Point Reactor

The Douglas Point reactor uses moderator dump as one of its safety shut-down mechanisms. Subsequent cooling of the calandria tubes is by sprays from headers at the top of the calandria which form falling films on the calandria tubes. Under LOCA conditions with impaired emergency coolant injection, these films must provide a heat sink for the decay heat of the fuel and for fuel channel stored heat, a function performed in other CANDU reactors which do not use moderator dump for shut-down purposes by the bulk moderator itself. The cooling effectiveness and stability of the films must be assured in this case. Potential mechanisms of film disruption are flow starvation, non-uniform surface tension effects (Marangoni instability) and film blow-off by bubble nucleation effects. Studies of these disruption mechanisms under conditions relevant to the Douglas Point reactor are described in references 1 and 4.

These studies indicated that two mechanisms of falling film disruption might exist for the conditions of concern here: Marangoni

instability and film blow-off by bubble nucleation. Approximate analyses of these mechanisms, based on modifications to empirical models for falling films on vertical surfaces, which have not been verified by experiment, have been developed in reference 1.

The analyses in reference 1 indicate that film disruption by Marangoni instability may occur at quite low heat fluxes, of the order of 10 W/cm^2, for conditions of concern here. However, Marangoni instability does not result in the film departing from the surface but in the film breaking up into rivulets which remain on the surface. Thus, adequate cooling is provided on the portions of the surface covered by the rivulets. Whether cooling of the rest of the surface is adequate will depend on the spacing and width of the rivulets (See reference 4).

The analyses of reference 1 also indicate that film blow-off by bubble nucleation, for relevant Douglas Point reactor conditions, will probably occur at local heat fluxes of about 100 to 135 W/cm^2.

To assess transient dry-patch behavior on the Douglas Point reactor calandria tubes, the modified version of IMPECC was run for Douglas Point conditions assuming that film critical conditions, i.e. complete film disruption, occurred at a local heat flux of 125 W/cm^2. This value is representative of the heat flux at film blow-off by bubble nucleation. The use of a critical heat flux of 125 W/cm^2 also provides a severe test of the modified IMPECC program, and was employed to evaluate the range of its applicability.

The quenching temperature for the present case will not be determined by the minimum film boiling temperature as in the case of a submerged

calandria tube, but will be governed by parameters similar to those governing conventional re-wetting by top-flooding (e.g., 10). The correlation of Yu has been recommended for use in such cases in the critical evaluation of the literature by Butterworth and Owen (10). To apply the correlation to determine the quenching temperature, the heat transfer coefficient in the wetted region must be known. For the correlations used in IMPECC and expected conditions behind the wetting front, the heat transfer coefficient just in the wetted region will be of the order of 3.5 W/cm^2K (.6000 $Btu/hr.ft^{2o}F$). The estimated quenching temperature for the present conditions, ignoring the beneficial effect of film sub-cooling and assuming a falling film Reynolds number of 4230 (1), is about 330^oC. Another approach to the prediction of the quenching temperature can also be taken. It has been observed that experimental quenching temperatures are about 100^oC less than the homogeneous nucleation temperature for the liquid in question (10). For heavy water at atmospheric pressure, the homogeneous nucleation temperature is about 310^oC, so that the quenching temperature will be about 210^oC. Considering these estimates, and that a lower value is more conservative in this case, a quenching temperature of 250^oC was assumed for this study.

The IMPECC program, as described earlier, uses the equation of Breen and Westwater to calculate the heat transfer coefficient over the dry patch. While this equation applies very well for a dry patch on a submerged calandria tube, where true film boiling occurs, it will not apply as well to a dry patch resulting from falling film blow-off, since in this case there will not be, in general, a bulk fluid separated by a thin vapor film from the calandria tube surface. However, the magnitude of the heat transfer

coefficients predicted by the Breen-Westwater correlation is quite low for the present conditions, about 0.015 W/cm^2K or 30 $Btu/hr.ft^{2\circ}F$, which will be of the magnitude of values which might be expected for the actual conditions. Therefore, no change was made to the program for the heat transfer coefficient for the dry-patch region.*

Results for the Douglas Point reactor (at 70% full power) are given in Figure 10, where the growth and shrinkage of the dry patch are shown. Although the general behavior is quite similar to that for the dry patches on a Bruce reactor calandria tube, as shown earlier, the maximum extent of the dry-patch is somewhat greater for the same quenching temperature (12° compared to 7.5°) and the time to re-wet is much longer, about 90 seconds compared to about 25 seconds. The maximum calandria tube temperature reached under the dry patch is about $702^\circ C$, a few seconds after PT/CT contact. There are some questions about the mathematical accuracy of the results obtained since the dry patch extended into the relatively coarse-mesh region of the model and some instabilities in the predictions of calandria tube surface temperature and heat flux occurred in the wetted region just beyond the edge of the dry patch just after it first reached its maximum predicted extent. These instabilities, which probably result from time steps that are too long, soon disappeared however.**

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* Note however, that when the Gillespie equation is substituted for the Breen-Westwater equation to predict film boiling under sub-cooled conditions, it probably should not be used for other than submerged calandria tubes.

** To reduce these mathematical uncertainties would require that the fine mesh be extended to about 20° and the time steps reduced further. Program runs would be even more expensive with these changes. The run described here required over 65 minutes of CPU time.

In spite of these uncertainties, the results obtained are probably reasonably accurate and provide a fairly realistic picture of the transient behavior of falling film blow-off by bubble nucleation followed by re-wetting by the film. The results are encouraging in that they show that, should a LOCA occur in the Douglas Point reactor with impaired emergency coolant injection, although the falling film would be blown off a calandria tube by bubble nucleation when the pressure tube sags onto the calandria tube, the dry area would not be very extensive and would re-wet in a reasonably short time. The maximum temperatures reached by the calandria tube are moderate, and higher than normal temperatures do not cover a large area nor persist for a long time. Therefore, we conclude that the integrity of the calandria tube will not be jeopardized during the transient film blow-off.

A comparison of predicted fuel, sheath and maximum PT temperatures for the present case of a transient dry patch, at the moment that the patch re-wets, to the temperatures at the same time after PT/CT contact for a previous case in which no film disruption occurred is given in Table 6. Table 6 shows that there is very little effect on fuel, sheath and maximum pressure tube temperatures, less than 15^{o}C at the most, of cooling film disruption even though the dry-patch formed does not completely re-wet for about 90 seconds.

The above results have been obtained for a fuel element power rating for the maximum rated element of 28 W/cm, corresponding to 70% of full power for the Douglas Point reactor. However, the transient dry patch behavior, being essentially a result of stored-heat effects rather than power-level effects will not be affected significantly by a change in power

TABLE 6

EFFECT OF FALLING FILM DISRUPTION ON FUEL,
SHEATH AND MAXIMUM PRESSURE TUBE TEMPERATURES

DOUGLAS POINT REACTOR

70% Full Power
(FEPR = 28 W/cm)

Time after PT/CT contact = 90 seconds

Component	Temperatures, °C	
	No Film Disruption	Film Disruption
F1	1401	1416
S1	1390	1405
$S2_i$	1378	1393
F2	1371	1385
$S2_o$	1318	1331
$S3_i$	1275	1288
F3	1240	1252
$S3_o$	1120	1132
PTmax.	998	1008

level. Therefore the results shown in Figure 10 and the maximum calandria tube temperature resulting from the transient dry patch will apply also for 100% full power. The fuel sheath and maximum PT temperatures for the transient dry patch case given in Table 6 will be affected to a somewhat greater extent but the maximum differences between these temperatures and those for the same power level without film disruption would be unlikely to be greater than about 25^{o}C at the most.

4.0 CONCLUSIONS

In this part of the report we have described the development of the modified IMPECC program which permits the analysis of the behavior of transient dry patches on a calandria tube, such as might result from critical heat flux followed by re-wetting for submerged calandria tubes or from falling film disruption followed by re-wetting for spray-cooled calandria tubes.

Major conclusions reached can be summarized as follows:

1) In the highly improbable event that CHF occurs on PT/CT sagging contact following a LOCA with impaired emergency coolant injection in a Bruce reactor, a dry patch would form and grow to a maximum extent of about 4 to 8 degrees on each side of the bottom of the calandria tube. The dry patch would re-wet within about 10 to 30 seconds. The maximum local calandria tube temperature reached would be less than 700°C. Calandria tube integrity would almost certainly be maintained. There would be negligible effects on fuel, sheath and maximum pressure tube temperatures. Pressure tube integrity would not be threatened.

2) The conclusions in 1) are based on the use of the Breen-Westwater correlation for film boiling, which ignores the beneficial effects of bulk moderator sub-cooling. When the Gillespie equation for film boiling under sub-cooled conditions is incorporated into the modified IMPECC program the predicted results for Bruce conditions will be even more favorable.

3) In the Douglas Point reactor, in which a LOCA with impaired emergency coolant injection will result in disruption of the falling films cooling

the calandria tubes, the analysis shows that, for film disruption by bubble nucleation, the dry patch formed following PT/CT sagging contact will reach a maximum extent of about 12° on each side of the bottom of the calandria tube. The dry patch will completely re-wet within about 90 seconds. The maximum local calandria tube temperature will be about $700^{\circ}C$. Calandria tube integrity will almost certainly be maintained. There will be small increases (less than $15^{\circ}C$ at the most) in fuel, sheath and maximum pressure tube temperatures above those that would otherwise occur. Pressure tube integrity will not be jeopardized. Although some numerical inaccuracy may have occurred in this analysis because of some nodes with a relatively coarse mesh and some time steps which were too long, this inaccuracy probably did not have very significant effects on the results.

4) Although the conclusions given in 3) were established from an analysis done for 70% full power, the transient dry-patch behavior and its effect on calandria tube temperatures and integrity will not be affected significantly by power level since dry-patch behavior is governed essentially by stored-heat effects rather than power-level effects. Fuel, sheath and maximum pressure tube temperatures at the moment of complete re-wetting will, at the most, be only slightly increased by the higher power level. Again, the integrity of the pressure tube will not be threatened by the occurrence of a dry patch.

5) Although the foregoing analyses have been done ignoring heat generated by the Zircaloy-water reaction, since the modified IMPECC, like the standard IMPECC, cannot account for this effect, the conclusions are valid

for all conditions including cases in which Zircaloy-water reactions would eventually occur. The reason for this conclusion is that the dry-patch behavior and its effect on calandria tube temperature, and thus integrity, is essentially governed by the effects of stored heat in the pressure tube at the time that the pressure tube sags onto the calandria tube. Since the pressure tube is assumed to sag onto the calandria tube at a given fixed temperature (1000^{o}C), stored heat effects will not be affected by whether the Zircaloy-water reaction occurs or not. With the Zircaloy-water exothermic reaction allowed for, the pressure tube would simply sag onto the calandria tube somewhat earlier in time.

Also, the analyses have shown very minor effects of transient dry patches on fuel, sheath and maximum pressure tube temperatures. The minor effects occur because of the very small areas and limited periods affected by the dry patches and by the poor thermal coupling between the outer surface of the calandria tube and the other components. These factors will still exist, of course, with the occurrence of the Zircaloy-water reaction. Therefore, we would again expect the occurrence of a transient dry patch to have very minor effects on fuel, sheath and maximum pressure tube temperatures should a Zircaloy-water reaction occur at these surfaces.

Part 2. Analysis of Accident Sequence S11: LOCA - LOECC - Loss of Moderator Cooling System

1.0 INTRODUCTION

In reference 2, the general approach to a study of potential accident sequences which could lead to core meltdown was described. Several accident sequences following a large LOCA were discussed and two were selected for detailed study, with a third to be studied if time permitted. An outline of the analytical approach and scope of the work on the first accident sequence, LOCA + LOECC + Loss of Moderator Cooling System, designated as S11 in reference 2, was then provided. The second accident sequence proposed for study, LOCA + LOECC + Loss of Moderator Heat Sink, designated as S13 in reference 2, is closely related to S11, so that many of the analytical models and much of the information developed for S11 can also be applied to or extended to S13. Also, some of this work will be relevant to the assessment of accident sequence S15, Failure to Shutdown, which was the accident sequence to be investigated if time permitted.

In this part of the report, work on the analysis of accident sequence S11 and the development of analytical models applicable to both accident sequences S11 and S13 are described.

2.0 DESCRIPTION OF ACCIDENT SEQUENCE S11: LOCA + LOECC + LOSS OF MODERATOR COOLING SYSTEM

In reference 2, the analytical approach to accident sequence S11 and the steps proposed for the development of the analysis of this sequence were described.

In the period covered by this report, considerable thought has been given to developing a detailed event sequence for the study. A comprehensive analytical flow chart has been established, as presented in Figure 11, which is divided into nine parts, Figures 11A to 11I. Connections between the parts of Figure 11 are indicated by corresponding numbers in the logic flow lines. The accident sequence is described briefly in this section of the report and may be followed in Figure 11. In later sections of the report, brief outlines of the analyses undertaken and results obtained for the various stages of the study, as illustrated in the flow chart of Figure 11, are given.

It should be noted that there are considerable uncertainties about some of the mechanisms involved in the various stages of this accident sequence, particularly after fuel melting occurs. In certain cases, bounding analyses and parametric analyses have been or will be necessary with judgment being applied on the likelihood of a given behavior.

In accident sequence S11, it is assumed that a stagnation-break LOCA has occurred and that emergency coolant injection fails. The moderator heat sink is present but the moderator cooling system fails (e.g., by a loss of service water to the moderator heat exchanger). The course of the subsequent sequence of events is somewhat speculative now of course; confirmation or amendment will emerge from the study itself. The study has already resulted in some clarification of the event sequence.

As stored and decay heat as well as heat generated by the Zircaloy-water reaction of the sheaths and the pressure tubes flows to the moderator its temperature increases. The increasing vapor pressure of the heavy water and the compression of the helium cover gas in the relief ducts as the moderator swells cause the rupture disks to break before the moderator boiling point is reached. No flashing of the moderator occurs when the rupture disks break since the moderator temperature at this time is below the saturation temperature corresponding to atmospheric pressure. However, a small fraction of the moderator later overflows from the relief ducts before moderator boiling begins because of the moderator swell caused by its temperature rise. Moderator boiling begins and moderator is lost from the calandria through the relief ducts both by boiling and by liquid entrainment in the two-phase flow in the calandria and relief ducts. This loss is compensated for to some extent by liquid inflow to the calandria from the external moderator circuit. Eventually the void fraction in the boiling moderator near the top of the calandria will result in a boiling crisis on, or uncovery of, the upper row of calandria tubes. Heat transfer from this upper row will then occur only by radiation to its surroundings and by convection to the steam flow over the tubes. The calandria tube temperature will then increase rapidly. Should the calandria tube temperature reach a sufficiently high level, a Zircaloy-water reaction of the calandria tube would ensue which would provide another heat source and cause a further increase of calandria tube temperature. Eventually, the calandria tube temperature may reach the melting point or it may peak below the melting

point and begin to decrease. The rapid increase in calandria tube temperature will cause the pressure tube temperature to increase also and either reach the melting point or reach a peak below the melting point and decrease. Similarly, the fuel and sheath temperatures may reach the melting points of UO_2 and Zircaloy. The temperature histories of these components subsequent to calandria tube uncovery will depend on the time at which uncovery occurs and the heat source contribution of the Zircaloy-water reaction.

Subsequently, the next lower rows of calandria tubes will be uncovered or undergo boiling crisis as the moderator continues to boil off.

As the upper rows of calandria tubes are uncovered, melting of the calandria tubes, pressure tubes, fuel and fuel sheaths may occur, as mentioned above. Molten fuel and structural materials would then drop into the remaining moderator. A vapor explosion may occur, although the conditions are such that a vapor explosion is highly unlikely, as will be shown later. Some quenching of any molten fuel and other material by the moderator will occur. Fission products from fuel that does melt will escape from the fuel channel to the reactor building. Steam and hydrogen from the Zircaloy-water reaction will also escape to the reactor building. The effects of the steam and hydrogen, including any burning of the hydrogen that may occur, may affect containment integrity.

Eventually, many fuel channels may melt and the molten pool of fuel and other materials may melt through the bottom of the calandria into the shield tank where, again, a vapor explosion may occur. Considerable quenching of any molten materials will also occur here. Finally, any remaining molten material may melt through the shield tank wall and concrete roof of the

fuelling machine duct and thus into the duct. From there, any remaining molten material may melt through the floor of the duct into the underlying rock, thus resulting in failure of containment; from the Rasmussen study (16), such melt-through containment impairments result in negligible releases of radioactivity to the environment. The consequences of a containment melt-through will depend on the nature of the underlying rock structure, of course.

3.0 ANALYSES COMPLETED OR IN PROGRESS

Although the analysis of accident sequence S11 has not yet been completed, considerable work has been done on the various steps of the sequence and various analytical tools have been developed. This section of the report will provide a brief progress report on this work. A detailed description of the analysis will eventually be provided in the final report on the study.

The descriptions of the work done and in progress will be keyed to the boxes shown in the logic flow chart of Figure 11 by the numbers in the boxes.

3.1 Establishment of Heat Source to Moderator as Function of Time

The steps contributing to the establishment of the heat source to the moderator as a function of time are listed in boxes 1 to 6 in Figure 11.

From an examination of channel power distributions in a Bruce-A reactor unit (e.g., 17), groupings of channels and appropriate average powers for the groups were established. Four groups of channels were chosen with the full-power average fuel element power ratings and other data for each group as given in Table 7.

The heat source term resulting from the Zircaloy-water reaction was established, as described in reference 2, from information obtained from WNRE. In the WNRE analysis, CHAN-2 was used to determine the heat generation rate as a function of time for the maximum power channel in a Bruce-A reactor unit following a LOCA with LOECC for late-stagnation conditions, in which pressure tube sagging would occur (18). The resulting heat generation rate versus time curve is shown in Figure 12, as given in reference 2.

TABLE 7

GROUPING OF CHANNELS AND CHARACTERISTICS OF EACH GROUP: BRUCE REACTOR

Group	No. of Channels	Full-Power Average FEPR, W/cm
1	40	30
2	160	27
3	160	21
4	120	18

The heat generation rate shown in Figure 12 applies for a steam flow rate in the channel, 12 gm/s, which results in the maximum temperature rises of the fuel sheaths because of the Zircaloy-water reaction, as explained in reference 2.

The Zircaloy-water heat generation rate given in Figure 12 was applied as an additional heat source to the decay heat term in the computer program IMPECC (3, 4). A modified version of IMPECC, IMPECC-Z was developed to incorporate this additional heat source. The additional heat source was distributed among the fuel rings in proportion to the amount of Zircaloy sheathing in each ring. The additional heat source term for each ring is triggered in IMPECC-Z when the maximum sheath temperature for that ring reaches a specified temperature*, which is an input to the program. A temperature of 1050°C was used for the Zircaloy-water reaction trigger temperature in the analyses described here.

The distribution of the Zircaloy-water reaction heat source over the fuel sheaths only, rather than the fuel sheaths and the pressure tube, is conservative since the heat actually generated in the pressure tube, which is accounted for in the heat source term shown in Figure 12, is assigned to the fuel sheaths and thus must flow over larger thermal resistances to reach the moderator, resulting in predicted fuel and sheath temperatures higher than would otherwise be the case. The predicted pressure tube temperature should also be somewhat conservative since, while the predicted

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* The three outer fuel rings of a 37-element bundle are represented in IMPECC by solid annular rings of fuel with annular Zircaloy sheaths on the inner and outer surfaces (3). The Zircaloy-water reaction heat source is triggered separately for the Zircaloy on each surface when its temperature reaches the specified temperature.

heat flow from the pressure tube to the calandria tube will be correct, the predicted outer sheath temperature of the outer fuel ring will be higher than would actually be the case which will cause the inner surface temperature of the pressure tube to be higher than actual because of radiation heat transfer.

The program IMPECC-Z was run for each grouping of channels as listed in Table 7 and the heat flows to the moderator as a function of time were determined. Since the pressure tubes in each grouping are predicted to sag at somewhat different times, a computer program, SUM, was developed to combine properly-weighted heat flow rates from the calandria tubes. The results are shown in Figure 13, where the total heat source rate to the moderator is plotted as a function of time. In Figure 13, the four peaks shown in the curve during the time that the heat source rate is increasing represent the rapid discharge of stored energy from the pressure tubes as those in each grouping sag onto the calandria tubes. Figure 13 shows that the peak power to the moderator reaches about 113 MW about 18 minutes after the initial pipe rupture occurs. The power to the moderator drops to about 80 MW in about 40 minutes.

As pointed out in reference 2, the procedure used in this analysis can only approximate the effects of the Zircaloy-water reaction since it ignored the actual temperature-dependent reaction rate. However, a more realistic modelling of the effect of this reaction would require a complex three-dimensional analysis rather than the two-dimensional IMPECC approach, as pointed out earlier (4). Nevertheless, the method described here should

provide a conservative but reasonable estimate of the heat transfer rate from the calandria tubes to the moderator as a function of time, accounting for stored heat, fission product decay heat and the Zircaloy-water reaction heat. The work on this part of the analysis is complete, and the program IMPECC-Z and SUM are available for any desired additional analyses.

3.2 Transient Heat Balance on the Moderator; Non-Boiling Conditions

The steps dealing with the moderator transient heat balance and derived effects under non-boiling conditions are listed in boxes 7 to 9b in Figure 11.

A transient heat balance on the moderator under non-boiling conditions has been developed, allowing for heat transfer from the moderator through the calandria wall to the shield tank water. It was assumed that the shield tank water cooling system remained effective and the shield tank water temperature was therefore constant during the accident sequence. Initially, the moderator was treated as a single lumped system at a uniform temperature. Assessment of the characteristics of the moderator under boiling conditions, as described in the next section of this report showed that it would be necessary, under boiling conditions, to allow for variations of conditions such as void fractions within the moderator. Therefore, a model in which the moderator is divided into a series of horizontal slices has been developed. Each of 24 slices includes the moderator volume associated with each of the 24 horizontal rows of calandria tubes. An additional slice allows for the moderator volume above the top row of tubes and in the relief ducts, which varies as the moderator swells on heating. Heat balance equations were

written for each slice which allow for proportional heat input rate, heat storage rate in the moderator, heat loss rate to the shield tank wall, heat storage rate in the shield tank wall and heat loss rate to the shield tank water. The model also allows for arbitrary heat transfer rates (mixing rates) between the moderator slices. A computer program, MODERATOR, has been written for this model.

The computer program calculates the pressure in the calandria at any time, allowing for the vapor pressure of the moderator and the partial pressure of the helium cover gas as it is compressed by the swell of the moderator as it heats. The program determines the time at which the rupture disks fail and reduces the pressure over the moderator to atmospheric at that time. The program calculates how much, if any of the moderator is lost by overflow from the relief ducts, because of moderator swell after the rupture disks fail. Finally, the program determines the time at which boiling of the moderator starts in each slice of the model and prints out this information.

The program is operational and two trial runs have been made for Bruce reactor conditions, one assuming no mixing and the other perfect mixing (uniform temperature) of the moderator. The pressures over the moderator as functions of time for each case as well as for the earlier lumped moderator model case are shown in Figure 14. Figure 14 shows that there is very little difference in the predicted pressure histories for the three cases, with the predicted times to rupture disk failure (at 20 psig) being about 10.2 minutes for the lumped model, about 10.6 minutes for the finite-difference model assuming no mixing of the moderator and about 10.8 minutes for the finite-difference model assuming perfect mixing of the moderator.

All models predict that there will be no flashing of the moderator upon rupture disk failure since the bulk moderator temperature is below the saturation temperature corresponding to atmospheric pressure at the time of rupture disk failure.

The finite-difference models predict that boiling will begin at about 12.8 minutes for the no-mixing case, in slices 5 to 11 from the top of the calandria (excluding the relief duct "slice") and at about 13.2 minutes for the perfect-mixing case in the top two slices (again excluding the relief duct "slice"). The amounts of moderator predicted to be spilled from the calandria by thermal expansion just before boiling begins are about 49 cu.ft. for the no-mixing case and about 51 cu.ft. for the perfect-mixing case.

3.3 Transient Heat Balance on the Moderator; Boiling Conditions

The steps dealing with the moderator transient heat balance and derived effects under boiling conditions are listed in boxes 10 to 17 of Figure 11.

The initial model for moderator boiling assumed uniform conditions throughout the calandria, as mentioned in the previous section of this report. Analysis based on this model indicated that it could not cope with the actual behavior of the moderator under boiling conditions in a realistic manner. Deficiencies of the model included the approximation of actual static head variation with a mean static head, the initiation of boiling at the same instant throughout the moderator with a resulting unrealistic void fraction distribution and the neglect of two-phase flow, entrainment and pressure drop characteristics in the calandria.

Therefore, a finite-difference model of the moderator, based on the non-boiling model discussed in the previous section, was developed. A detailed logic flow diagram was established to assist in this process. For each moderator slice, the program allows for the power input from the calandria tubes, energy storage rate in the liquid, heat flow rate to the calandria wall, heat storage rate in the calandria wall, heat transfer rate from the calandria wall to the shield tank water, liquid and vapor inflow rates from the moderator slice below, liquid inflow rate from the moderator circuit, if appropriate, and liquid and vapor outflow rates from the slice to the slice above. A drift-flux model is used for the two-phase flow. Liquid entrainment rate in the outflowing vapor is determined by iteration, from which the average void fraction for the slice is determined. The friction, static head and momentum pressure drops across the slice are determined, from which the pressure at the top of the slice is calculated. This procedure is followed starting from the uppermost slice for each time increment. Similar calculations are made for the two-phase flow conditions in the relief ducts. From this information the pressure, void fraction and liquid hold-up profiles over the height of the calandria can be determined for any given time.

The equations for this analytical model have been developed and a computer algorithm established. However, the algorithm has not yet been implemented in a computer program. When this has been done successfully, it will be possible to determine the time at which the top row of calandria tubes becomes effectively uncovered by liquid moderator either by the drop

in effective liquid level or by the occurrence of a critical heat flux condition. Similarly, the program output will predict the times at which lower rows of tubes become uncovered.

3.4 Thermal Analysis of Uncovered Calandria Tubes

The steps dealing with the behavior of uncovered calandria tubes are listed in boxes 18 to 22 of Figure 11.

Once a calandria tube has become uncovered or has undergone critical heat flux, the mechanisms of heat transfer from the tube will be either film boiling or convection to the steam flow generated by lower tubes and radiation to the surroundings. To permit analysis of the thermal behavior of the calandria tube under these conditions, another variation of the program IMPECC has been developed, IMPECC-UCZ. This variation allows for a sudden change from nucleate boiling heat transfer to steam cooling and radiation heat transfer from the calandria tube at a selected time. The time at which this heat transfer deterioration occurs is an input to the program and will be determined from the results of the analysis described in Section 3.3 of this report. This modification to IMPECC also allows for heat generated by a Zircaloy-water reaction occurring between the steam flow and the calandria tube. The Zircaloy-water reaction model used in this case is a realistic one based on the solid-phase diffusion-controlled reaction (4) rather than the simplified model used for the sheaths and pressure-tube Zircaloy-water reactions, since the steam flow is essentially two-dimensional in this case as is the IMPECC model.

IMPECC-UCZ is operational and two test cases have been run successfully, one without and one with allowance for the calandria tube Zircaloy-water reaction.

The results of these cases have not been assessed completely yet and no definitive conclusions can be drawn now.

3.5 Assessment of Vapor Explosions and Molten Fuel Quenching in the Moderator, Shield Tank and Fuelling Machine Duct

The steps dealing with these assessments for the moderator are listed in boxes 23 to 29 of the logic flow chart of Figure 11. Related steps are listed in boxes 33 to 37 and boxes 49 to 52 of Figure 11.

An extensive review of the literature on vapor explosions has been completed. Of the works consulted in this survey, those listed as references 19 to 26 were among the most useful. The findings and conclusions of this review with respect to vapor explosions in the moderator, in the shield tank water and in water in the fuelling-machine duct will be described in detail in the final report on this study to be issued after completion of the analyses of accident sequences S11, S13 and S15.

A tentative conclusion from this review and the analyses based on it is that a vapor explosion is highly unlikely to occur in the moderator should molten fuel and other material drop into it from melting fuel channels above the effective moderator level. This tentative conclusion is based on the following facts:

a) The moderator will be at its saturation temperature. No vapor explosions have been observed when the volatile liquid is at its saturation temperature.

b) A necessary condition for a vapor explosion is that the initial interface temperature between the molten fuel or other molten material and the moderator must be above the melting point of

the high-temperature material. Calculations for the present situation indicates that this condition will not be met for UO_2.

c) Because any melting of fuel and structural materials that may occur will be gradual as the calandria tubes are slowly uncovered and the fuel channels heat up slowly, the rate of energy supply in the molten material will be very low so that any potential molten-fuel-coolant-interaction (MFCI) will not be very energetic, particularly since theory shows that for small mass ratios of molten liquid to volatile liquid, the efficiency of MFCI will be very low.

d) No experiments on mixing of UO_2 with water reported so far have resulted in vapor explosions (20).

e) Inertial and mechanical constraints of any possible mixture of molten materials and moderator will be minimal.

No work has yet been done on incorporation of the heat source from the quenching of molten fuel and other material, box 24, so that the steps shown in boxes 25 to 29 cannot yet be computed. However, it will be a relatively simple matter to incorporate such a heat source term in the program MODERATOR, described earlier. This modification will be done, as needed, following the analysis of moderator behavior under boiling conditions (boxes 11 to 17) and the analysis of uncovered calandria tube behavior (boxes 19 to 20b). Such modification of MODERATOR will permit the analytical steps shown in boxes 25 to 28b to be completed.

No assessment has been made yet of the possible occurrence or consequences of vapor explosions because of molten material mixing with the

shield tank water, boxes 33 to 37, or with water in the fuelling machine duct, boxes 49 to 52. It is possible that such assessments may not be necessary since earlier analyses may show that molten material may not mix with water in these two regions.

3.6 Assessment of Behavior of Molten Heat Source at Bottom of Calandria and in Shield Tank

The analytical steps dealing with this assessment for the calandria are listed in boxes 30 to 32 and for the shield tank are listed in boxes 38 to 44.

A literature survey on heat transfer mechanisms in molten materials and on the freezing-melting behavior of such materials in contact with cooled structural materials has been undertaken. Except for some preliminary hand calculations, no analysis of the thermal behavior of molten materials in contact with cooler structural surfaces has been done, pending the results of prior analyses which will be necessary to establish rates and timing of formation of molten materials and their transport to the structural surfaces. It may be established that such problems do not arise, at least as described in the scenario of Figure 11. However, it may be useful to analyze the potential behavior of molten materials within a reasonably well-cooled pressure tube to provide better knowledge of the behavior of a single fuel channel before calandria tube uncovery. The information and methods developed in this part of the study would be helpful for such an analysis.

3.7 Additional Assessments

The major assessments in addition to those discussed in the foregoing sections are those dealing with potential effects on containment at several

places in the accident sequence, with the interaction of molten mass with concrete (box 46) and with the melting of a mass through the floor and the underlying rocks (box 53). No work has been done on these assessments yet.

4.0 CONCLUSION

Progress on the analysis of accident sequence S11 has been described. The work to date has been concentrated on the development of the necessary analytical tools, and thus few significant conclusions can yet be drawn. Several of the analytical tools developed will also be useful in the analyses of accident sequences S13 and S15. It is anticipated that analyses of all of these accident sequences will be completed in the next study period.

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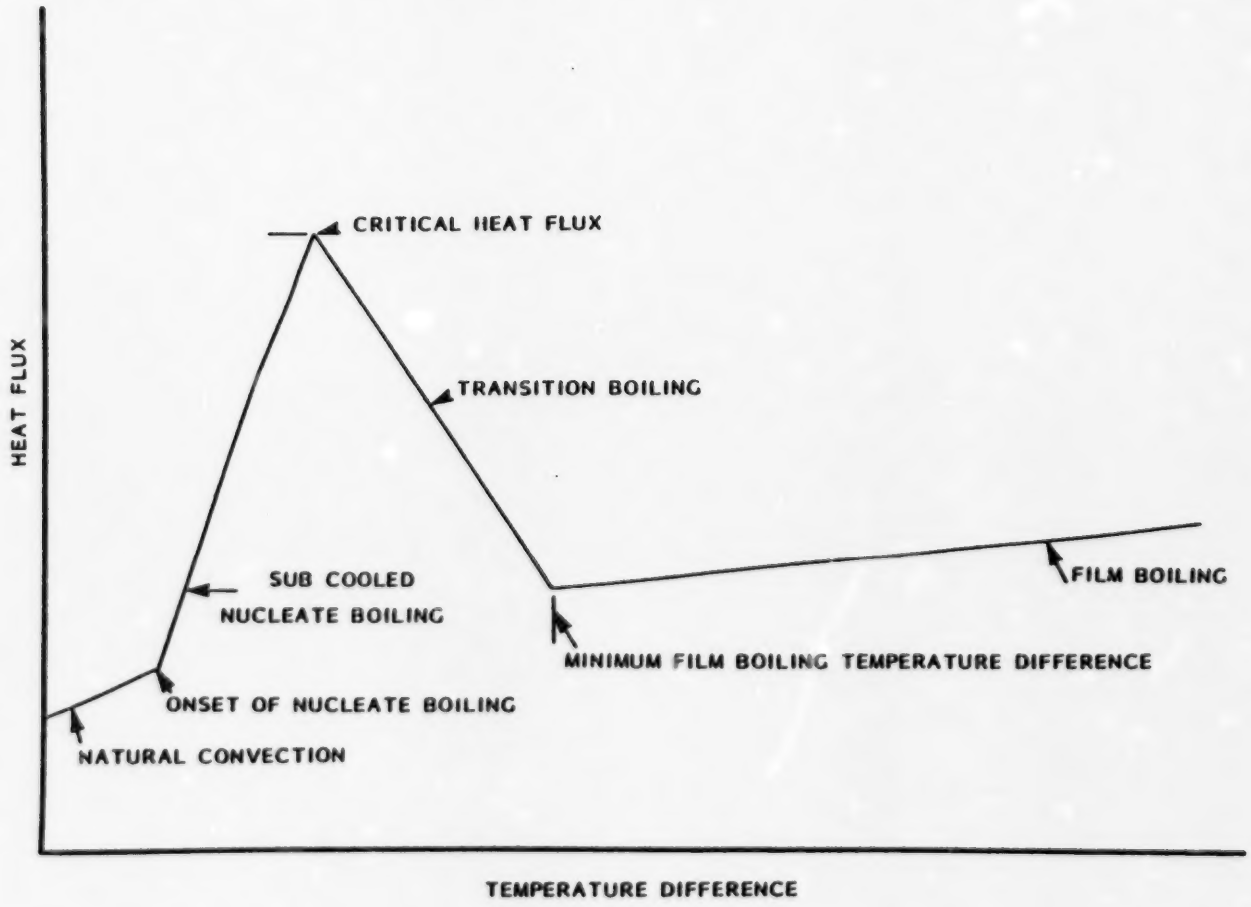


FIG. 1 HEAT TRANSFER REGIMES ON CALANDRIA TUBES

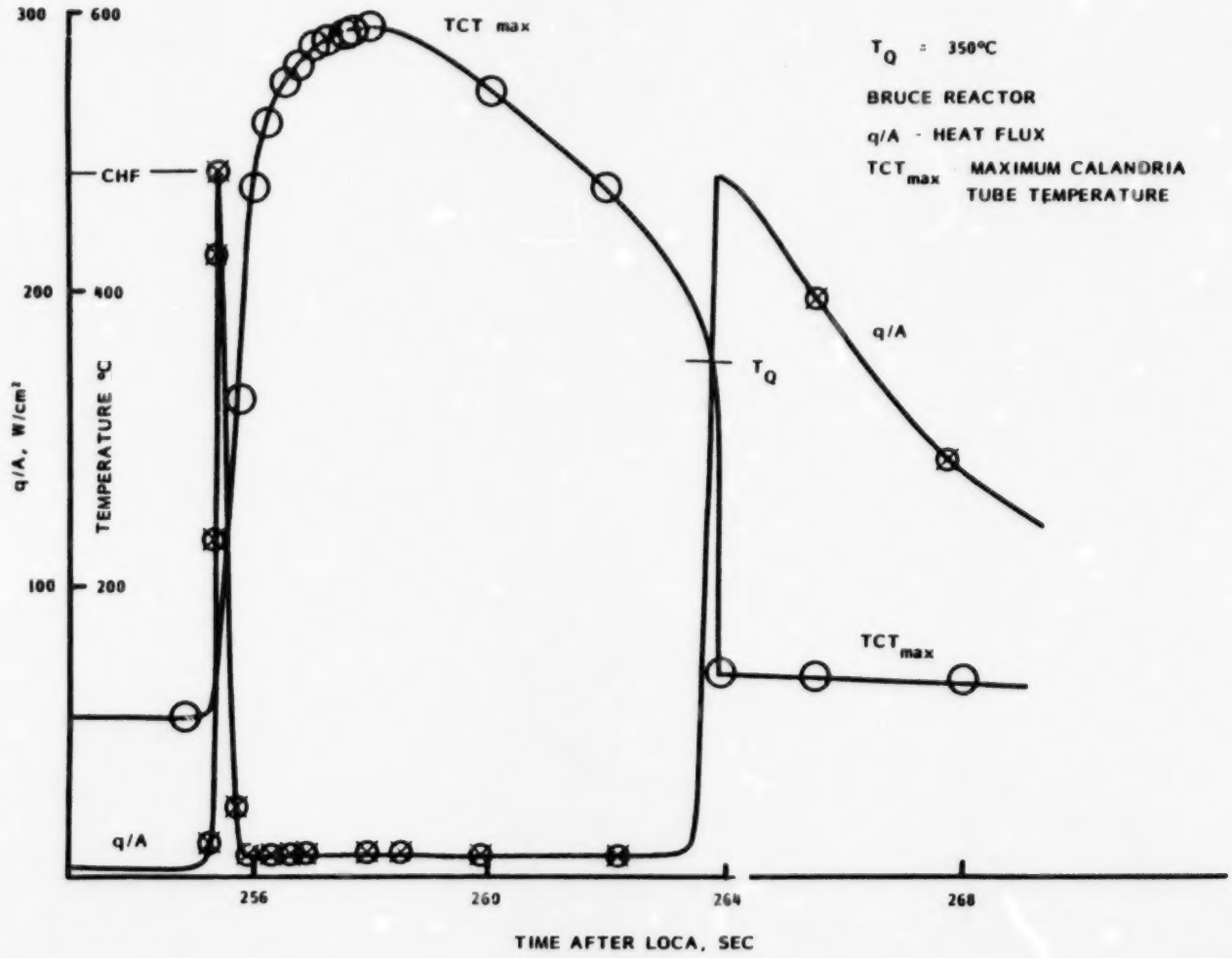


FIG. 2 EFFECT OF CHF ON CALANDRIA TUBE TEMPERATURES AND HEAT FLUXES AT BOTTOM OF CALANDRIA TUBE

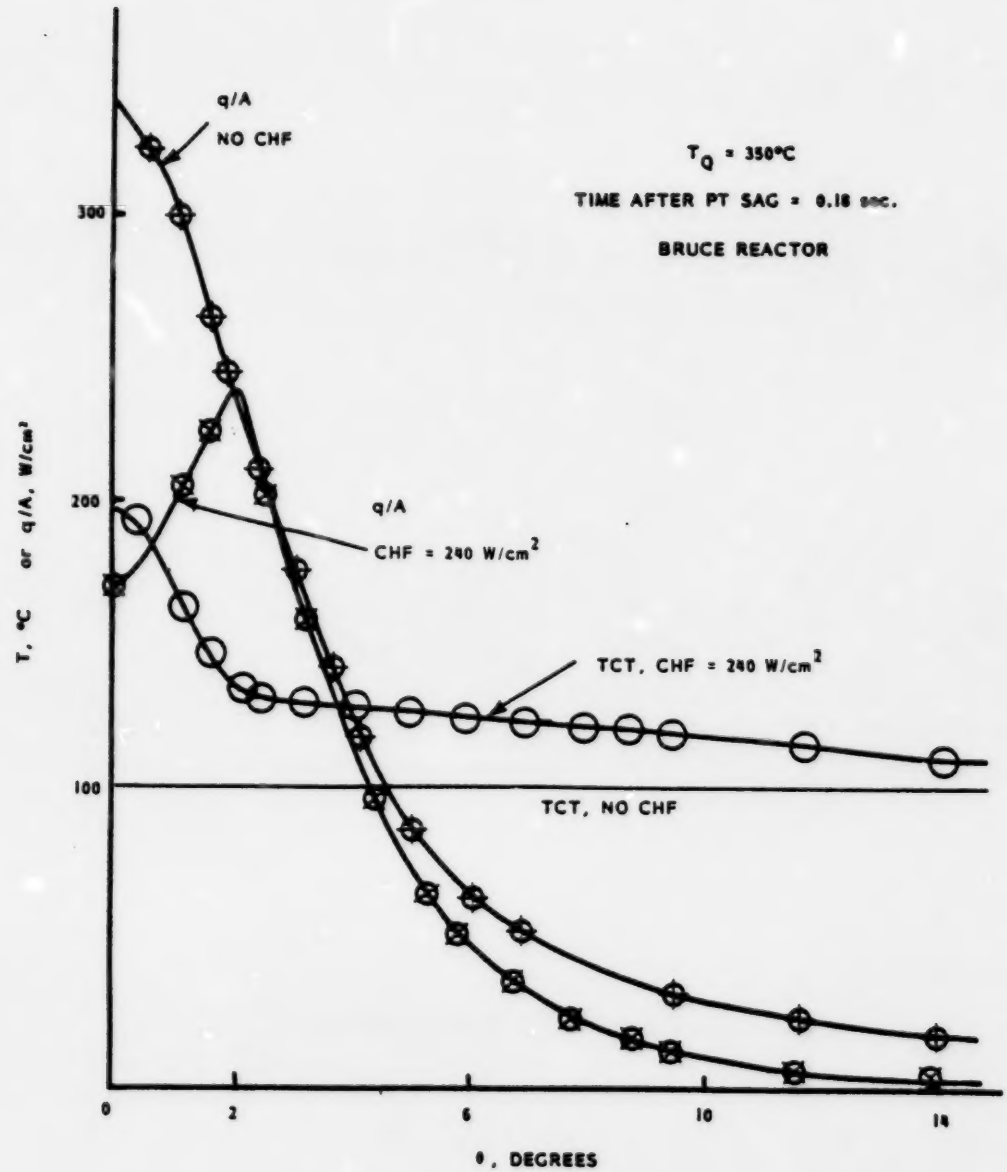


FIG. 3 EFFECT OF CHF ON CALANDRIA TUBE

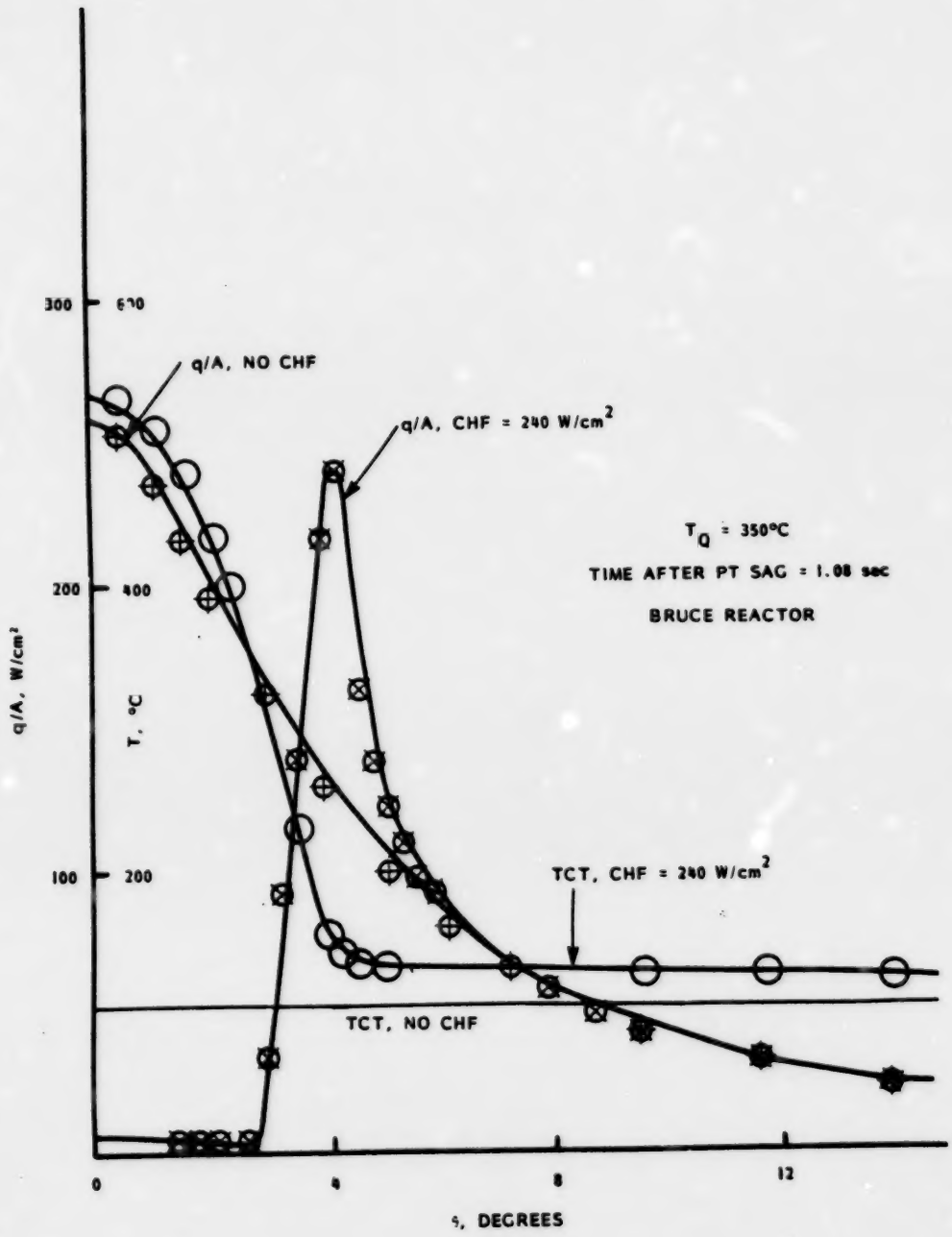


FIG. 4 EFFECT OF CHF ON CALANDRIA TUBE

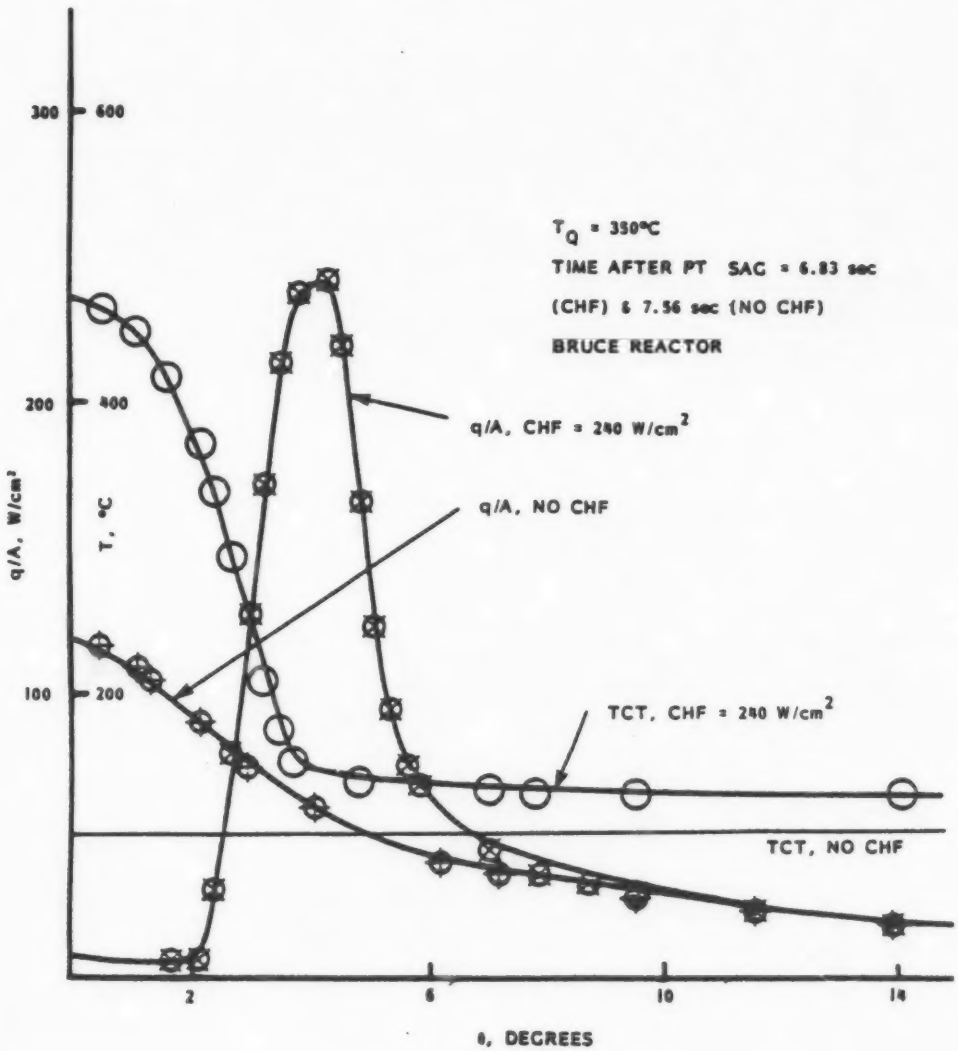


FIG. 5 EFFECT OF CHF ON CALANDRIA TUBE

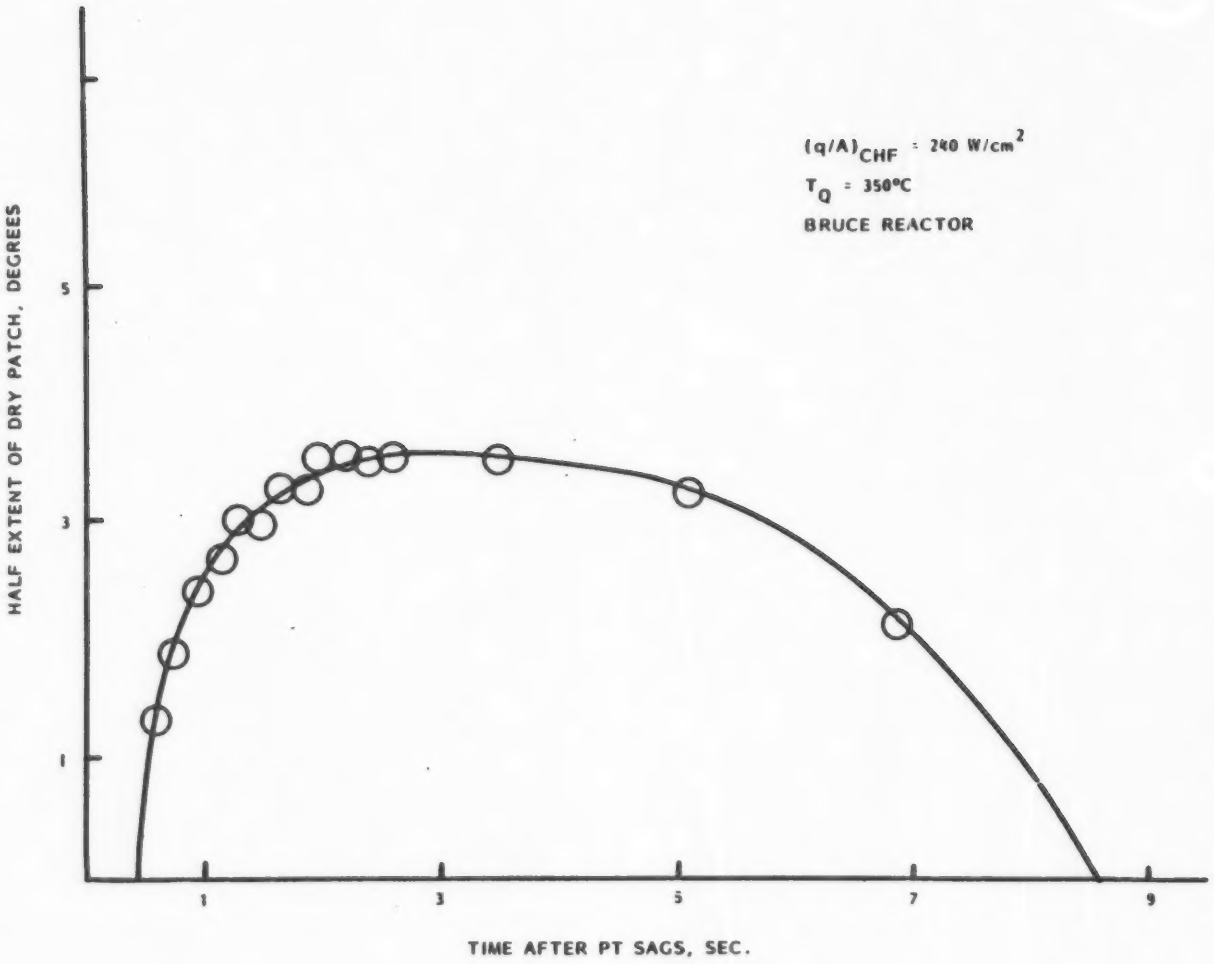


FIG. 6 GROWTH AND SHRINKAGE OF DRY PATCH

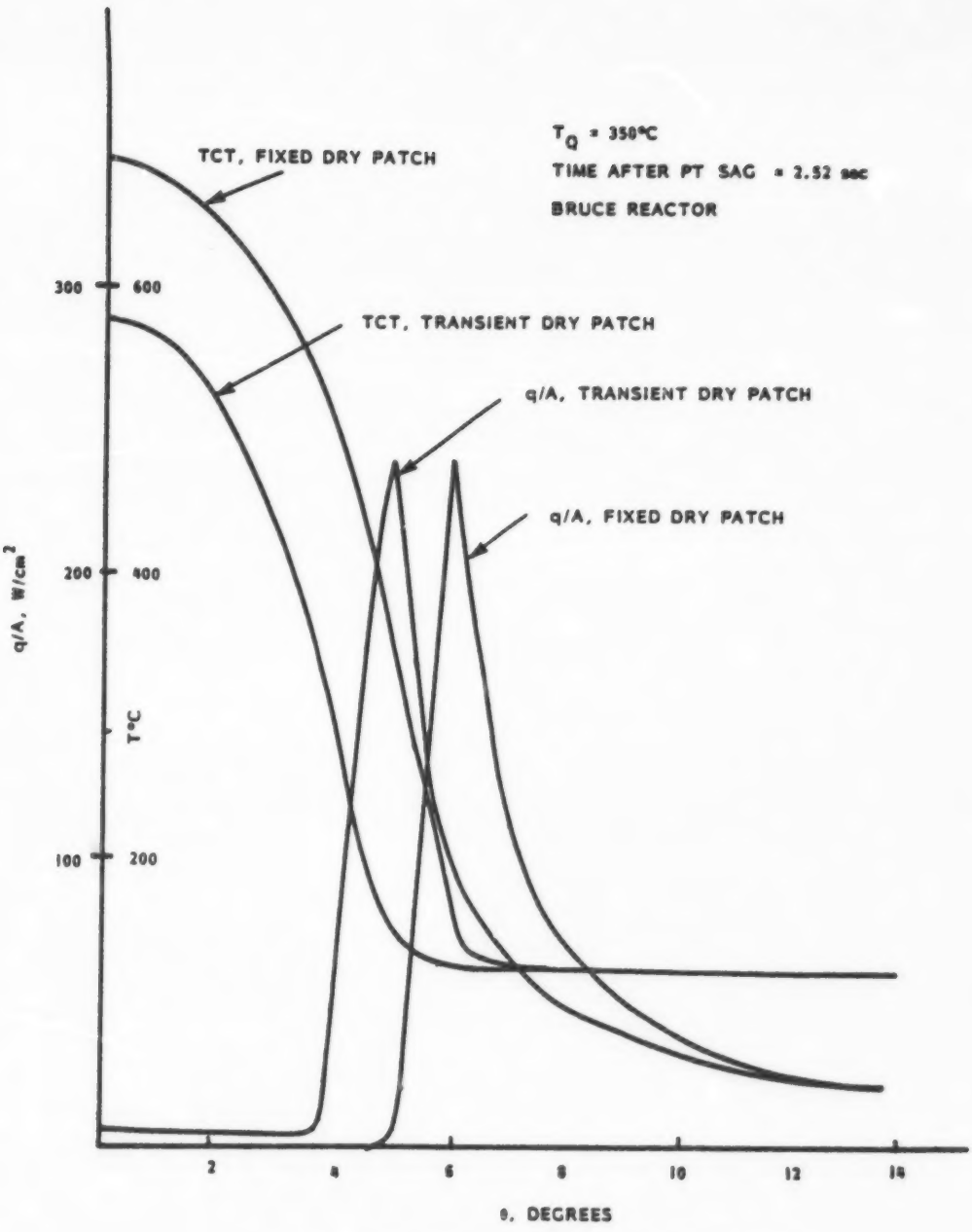


FIG. 7 COMPARISON OF CALANDRIA TUBE TEMPERATURES & HEAT FLUXES FOR FIXED AND TRANSIENT DRY PATCHES

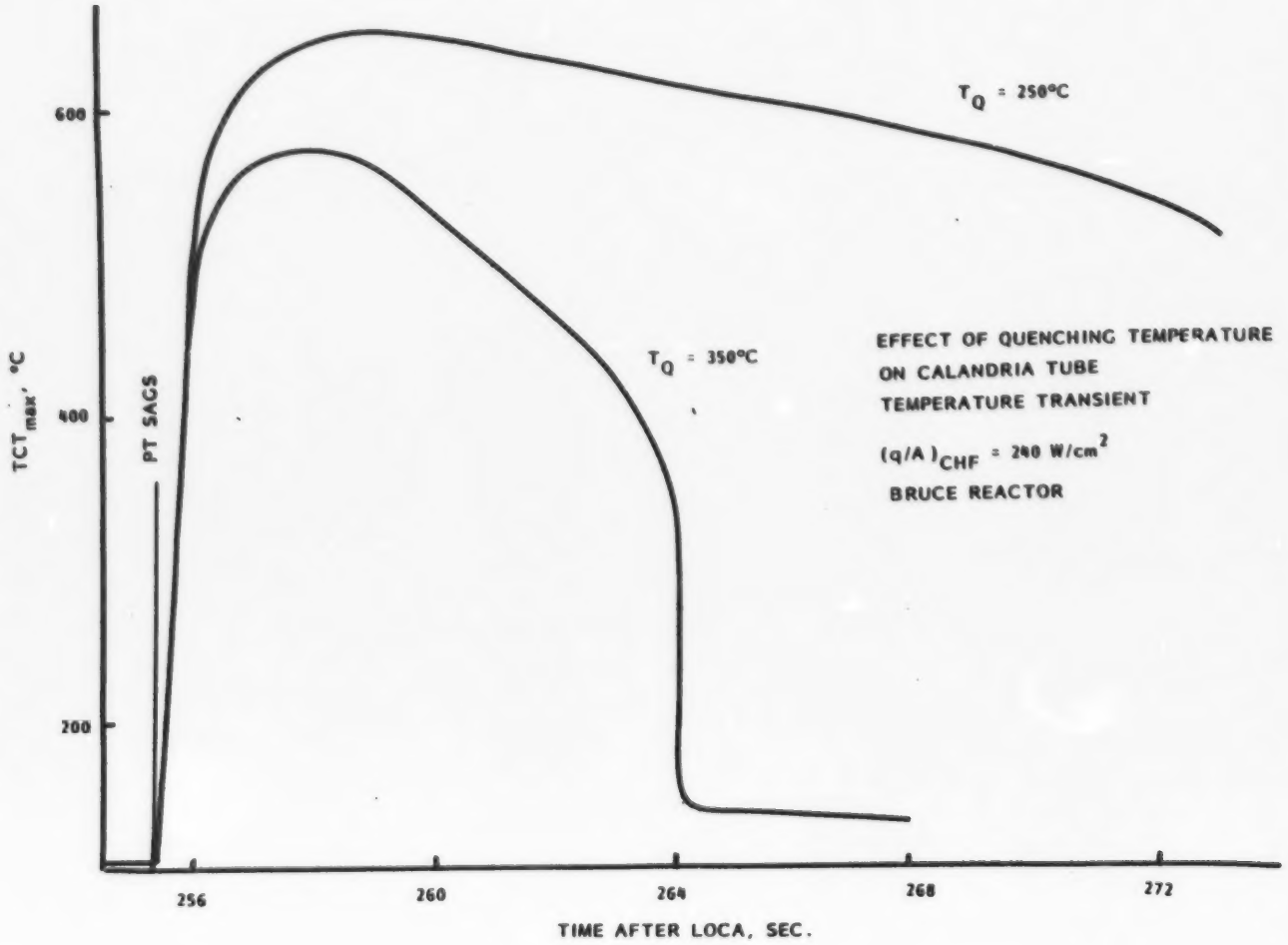


FIGURE 8 EFFECT OF QUENCHING TEMPERATURE ON CALANDRIA TUBE TEMPERATURE TRANSIENT

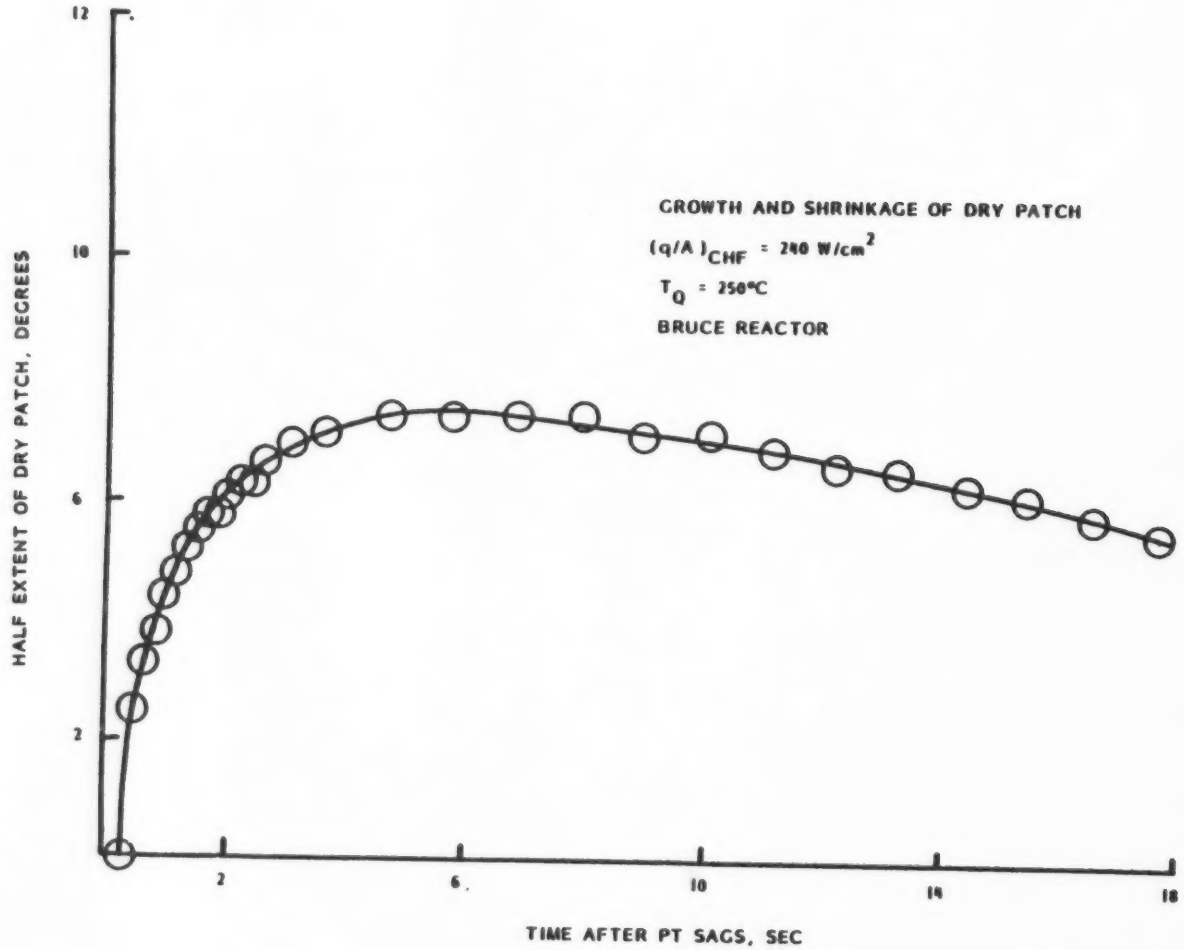


FIGURE 9 GROWTH AND SHRINKAGE OF DRY PATCH

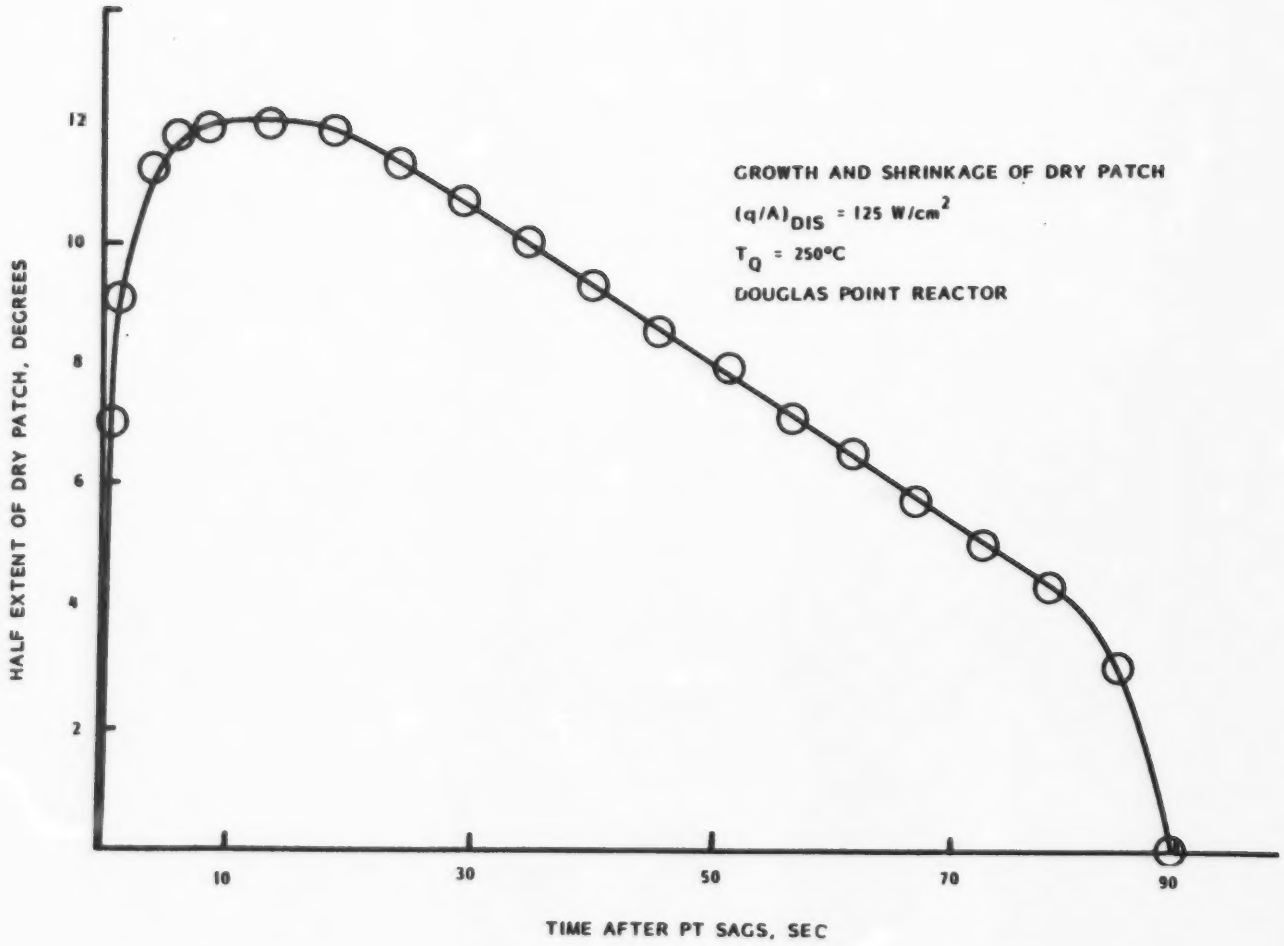


FIGURE 10 GROWTH AND SHRINKAGE OF DRY PATCH

Fig. 11

CANDU MELTDOWN STUDY
ACCIDENT SEQUENCE S11

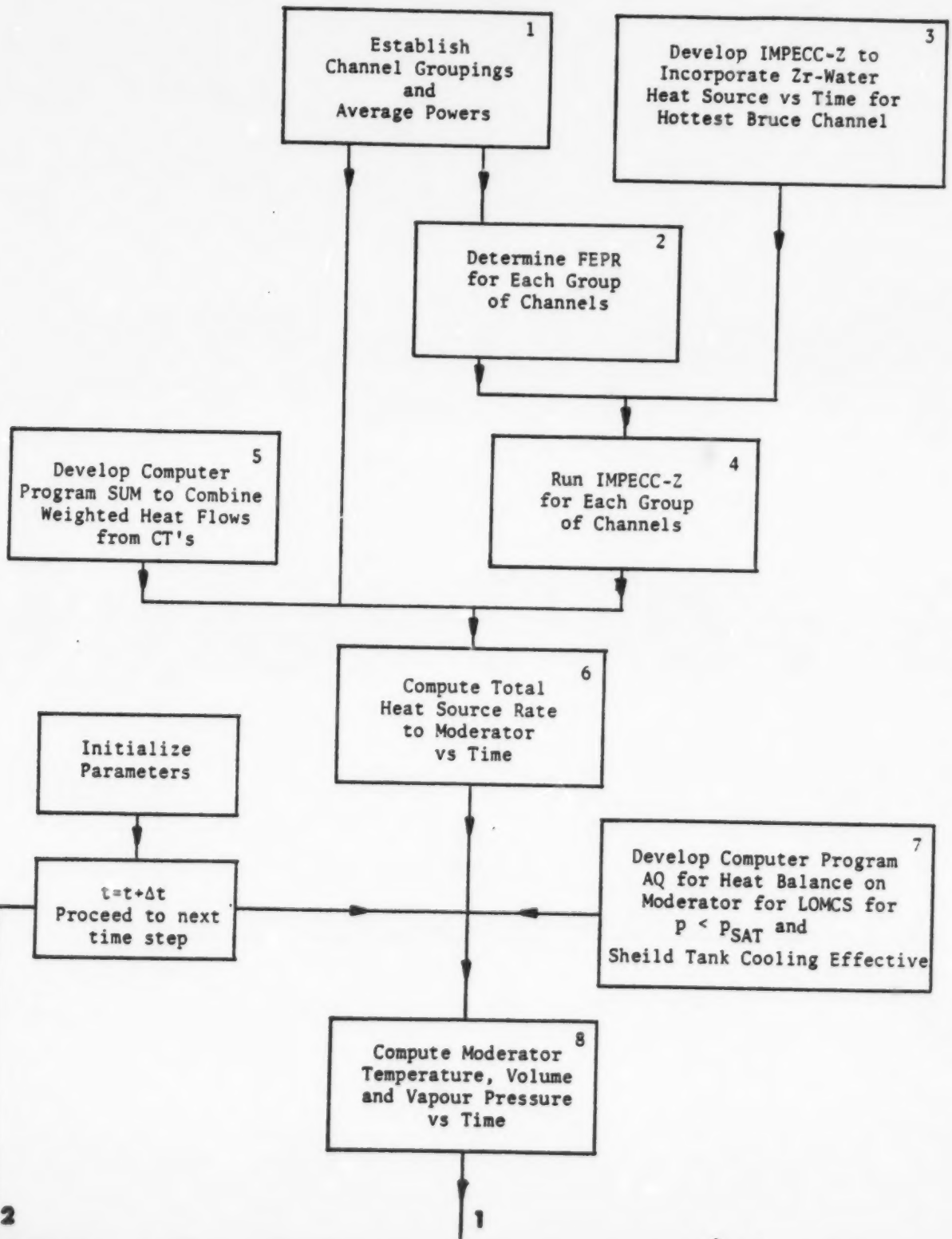
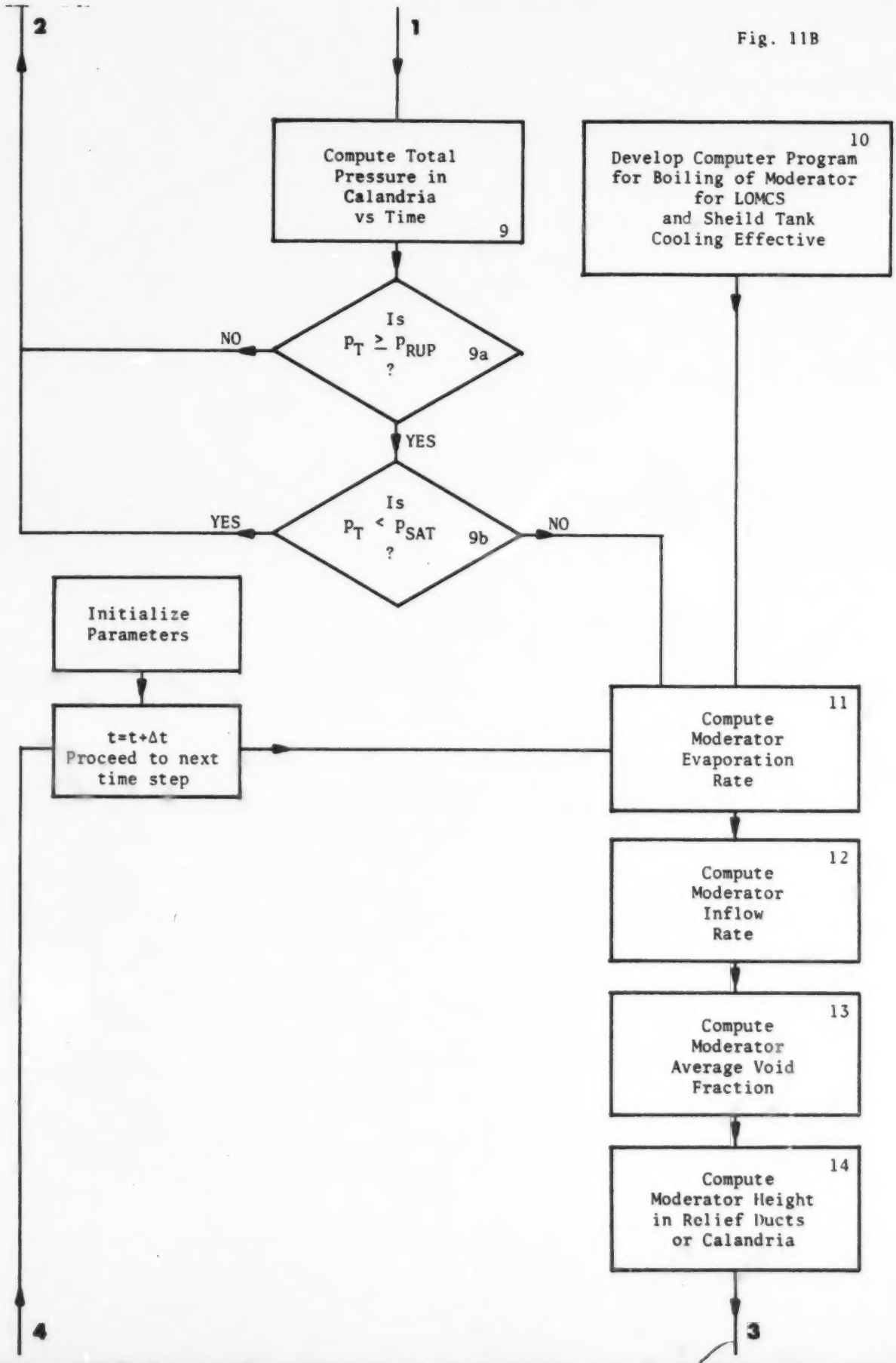

1
Establish Channel Groupings and Average Powers
3
Develop IMPECC-Z to Incorporate Zr-Water Heat Source vs Time for Hottest Bruce Channel
2
Determine FEPR for Each Group of Channels
5
Develop Computer Program SUM to Combine Weighted Heat Flows from CT's
4
Run IMPECC-Z for Each Group of Channels
6
Compute Total Heat Source Rate to Moderator vs Time
Initialize Parameters
t=t+Δt
Proceed to next time step
7
Develop Computer Program AQ for Heat Balance on Moderator for LOMCS for p < P_SAT and Sheild Tank Cooling Effective
8
Compute Moderator Temperature, Volume and Vapour Pressure vs Time
2
1

Fig. 11B


2
1
Compute Total Pressure in Calandria vs Time
9
10
Develop Computer Program for Boiling of Moderator for LOMCS and Sheild Tank Cooling Effective
Is $P_T \geq P_{RUP}$?
9a
NO
YES
Is $P_T < P_{SAT}$?
9b
YES
NO
Initialize Parameters
t=t+Δt Proceed to next time step
11
Compute Moderator Evaporation Rate
12
Compute Moderator Inflow Rate
13
Compute Moderator Average Void Fraction
14
Compute Moderator Height in Relief Ducts or Calandria
4
3

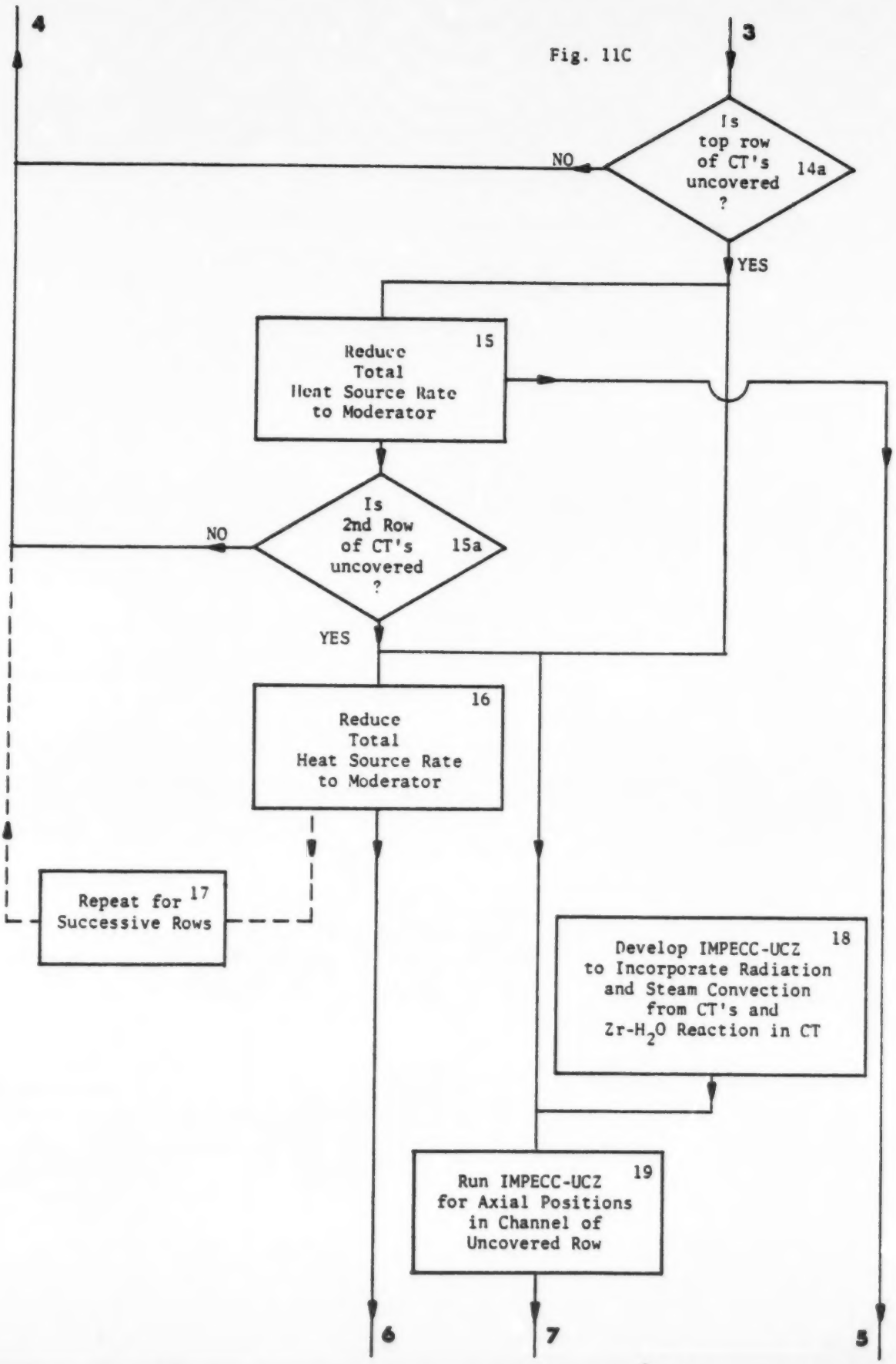

4
3
Fig. 11C
Is top row of CT's uncovered ? 14a
NO
YES
Reduce Total Heat Source Rate to Moderator 15
Is 2nd Row of CT's uncovered ? 15a
NO
YES
Reduce Total Heat Source Rate to Moderator 16
Repeat for Successive Rows 17
Develop IMPECC-UCZ to Incorporate Radiation and Steam Convection from CT's and Zr-H_2O Reaction in CT 18
Run IMPECC-UCZ for Axial Positions in Channel of Uncovered Row 19
6
7
5

Fig. 11D

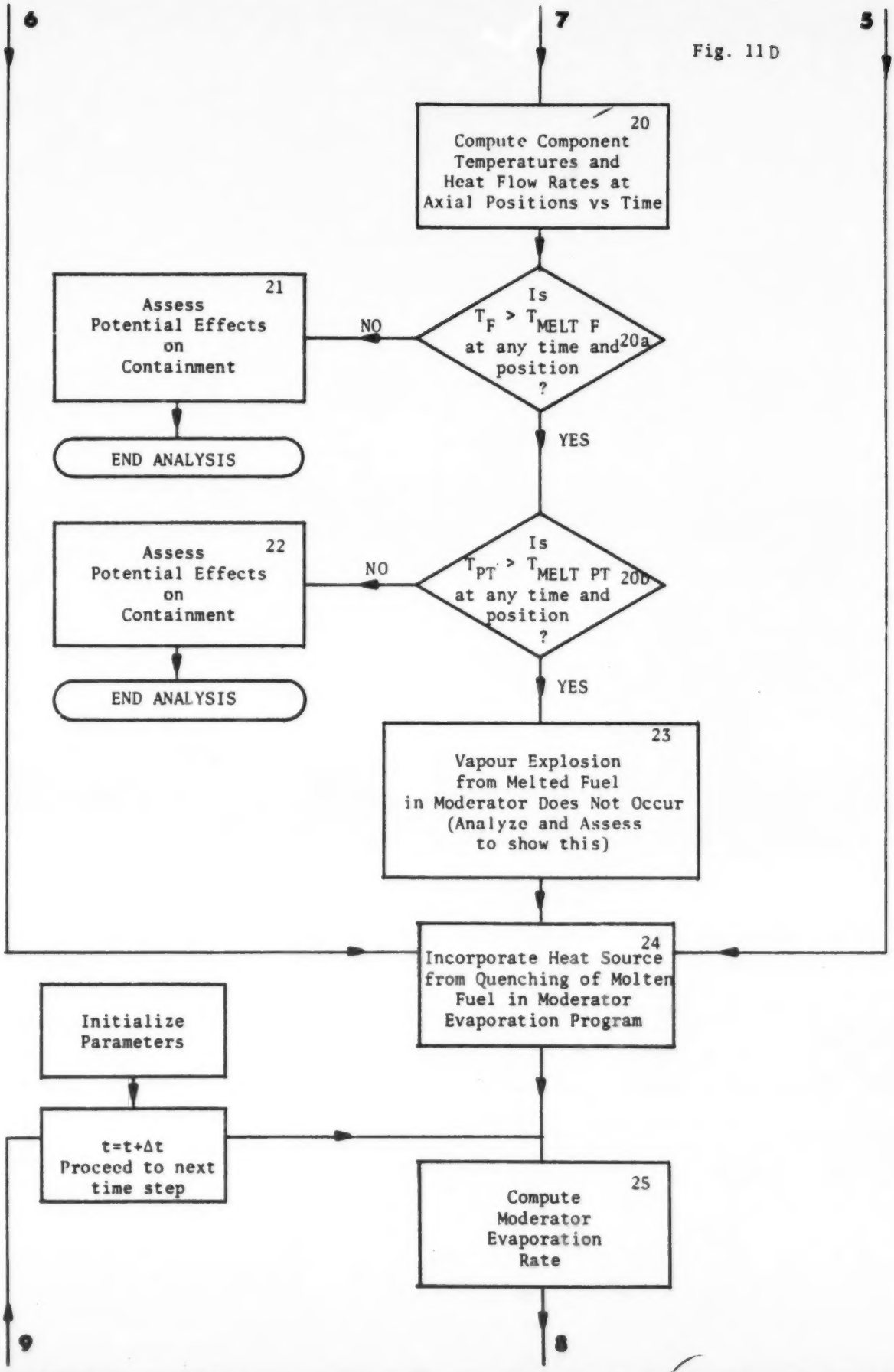

6
7
5
20
Compute Component Temperatures and Heat Flow Rates at Axial Positions vs Time
Is $T_F > T_{MELT\ F}$ at any time and position ? 20a
NO
21
Assess Potential Effects on Containment
END ANALYSIS
YES
Is $T_{PT} > T_{MELT\ PT}$ at any time and position ? 20b
NO
22
Assess Potential Effects on Containment
END ANALYSIS
YES
23
Vapour Explosion from Melted Fuel in Moderator Does Not Occur (Analyze and Assess to show this)
24
Incorporate Heat Source from Quenching of Molten Fuel in Moderator Evaporation Program
Initialize Parameters
t=t+Δt Proceed to next time step
25
Compute Moderator Evaporation Rate
9
8

Fig. 11E

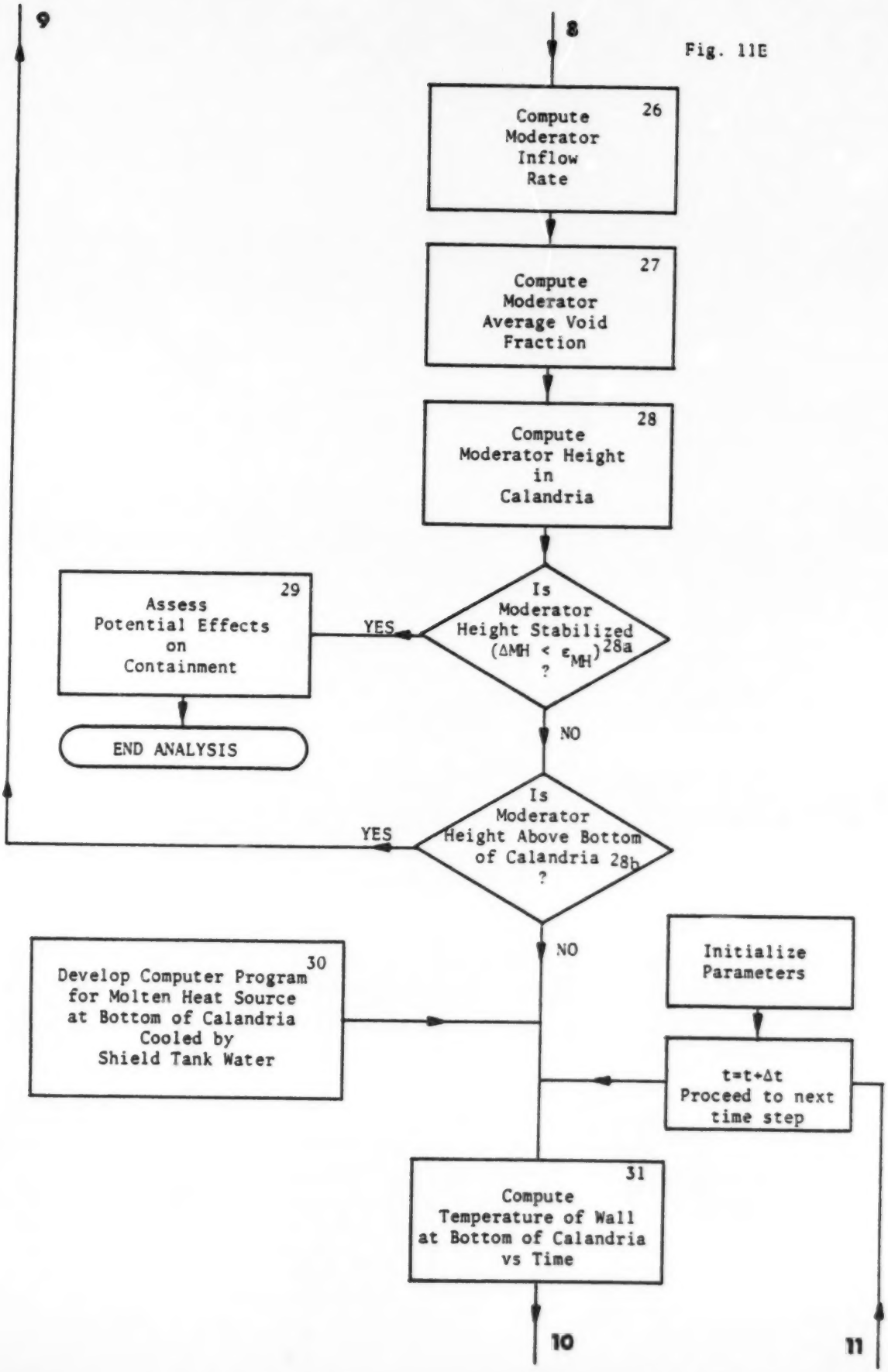
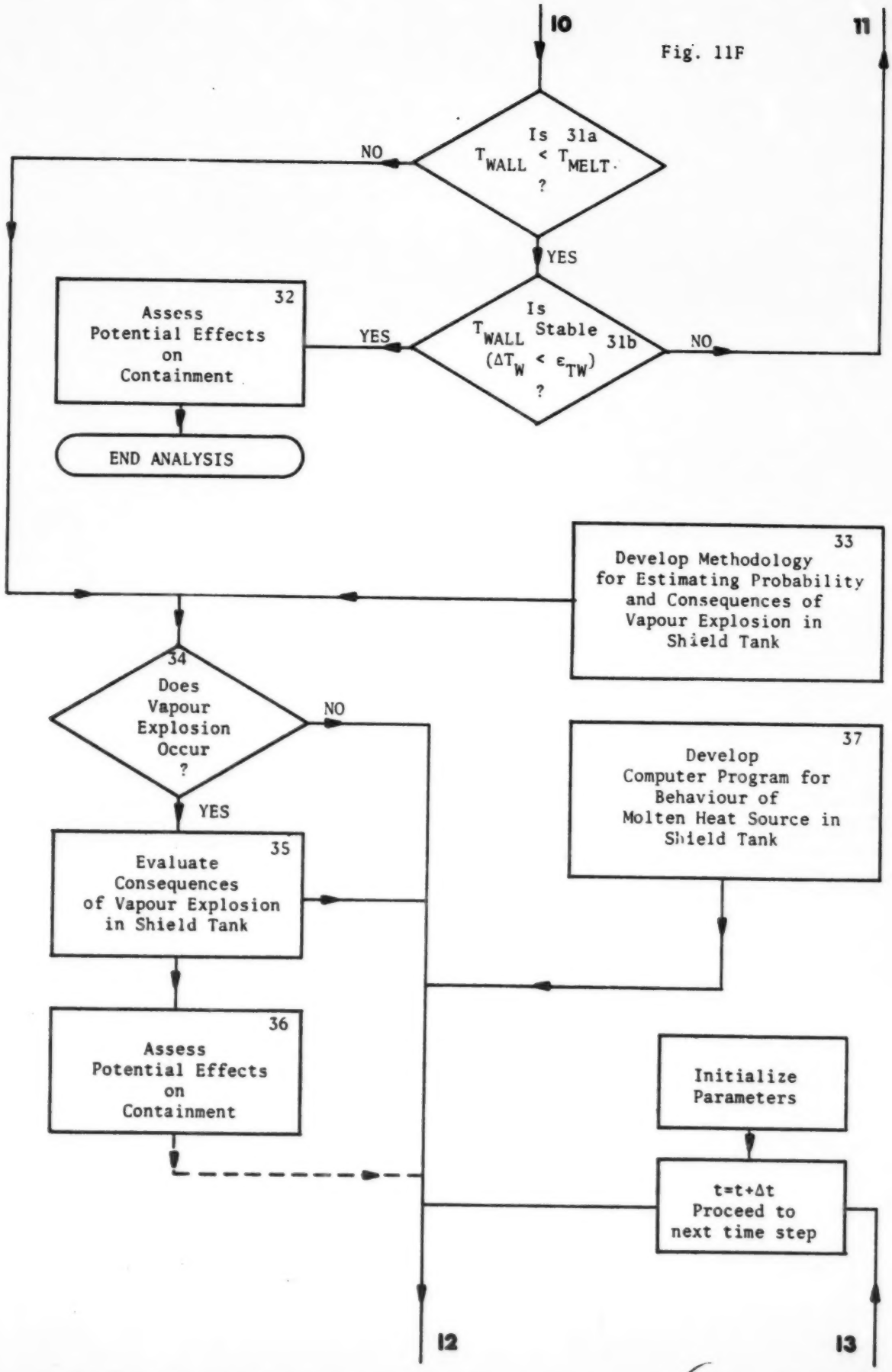

9
8
Compute Moderator Inflow Rate
26
Compute Moderator Average Void Fraction
27
Compute Moderator Height in Calandria
28
Is Moderator Height Stabilized ($\Delta MH < \epsilon_{MH}$) ?
28a
YES
Assess Potential Effects on Containment
29
END ANALYSIS
NO
Is Moderator Height Above Bottom of Calandria ?
28b
YES
NO
Develop Computer Program for Molten Heat Source at Bottom of Calandria Cooled by Shield Tank Water
30
Initialize Parameters
t=t+Δt Proceed to next time step
Compute Temperature of Wall at Bottom of Calandria vs Time
31
10
11

Fig. 11F


10
11
Is $T_{WALL} < T_{MELT}$? 31a
NO
YES
Is T_{WALL} Stable ($\Delta T_W < \varepsilon_{TW}$) ? 31b
YES
NO
32
Assess Potential Effects on Containment
END ANALYSIS
33
Develop Methodology for Estimating Probability and Consequences of Vapour Explosion in Shield Tank
34
Does Vapour Explosion Occur ?
NO
YES
35
Evaluate Consequences of Vapour Explosion in Shield Tank
36
Assess Potential Effects on Containment
37
Develop Computer Program for Behaviour of Molten Heat Source in Shield Tank
Initialize Parameters
t=t+Δt
Proceed to next time step
12
13

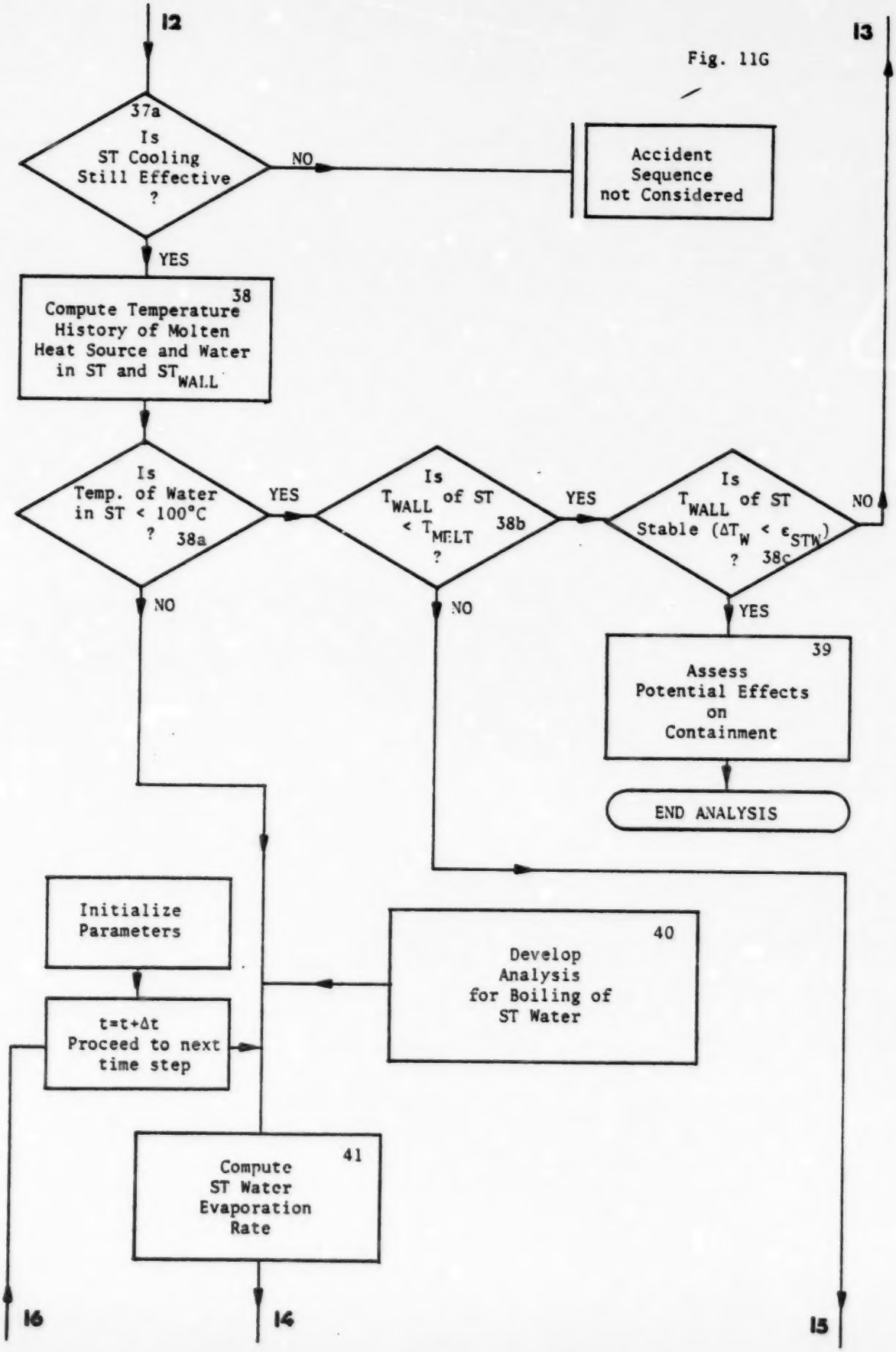
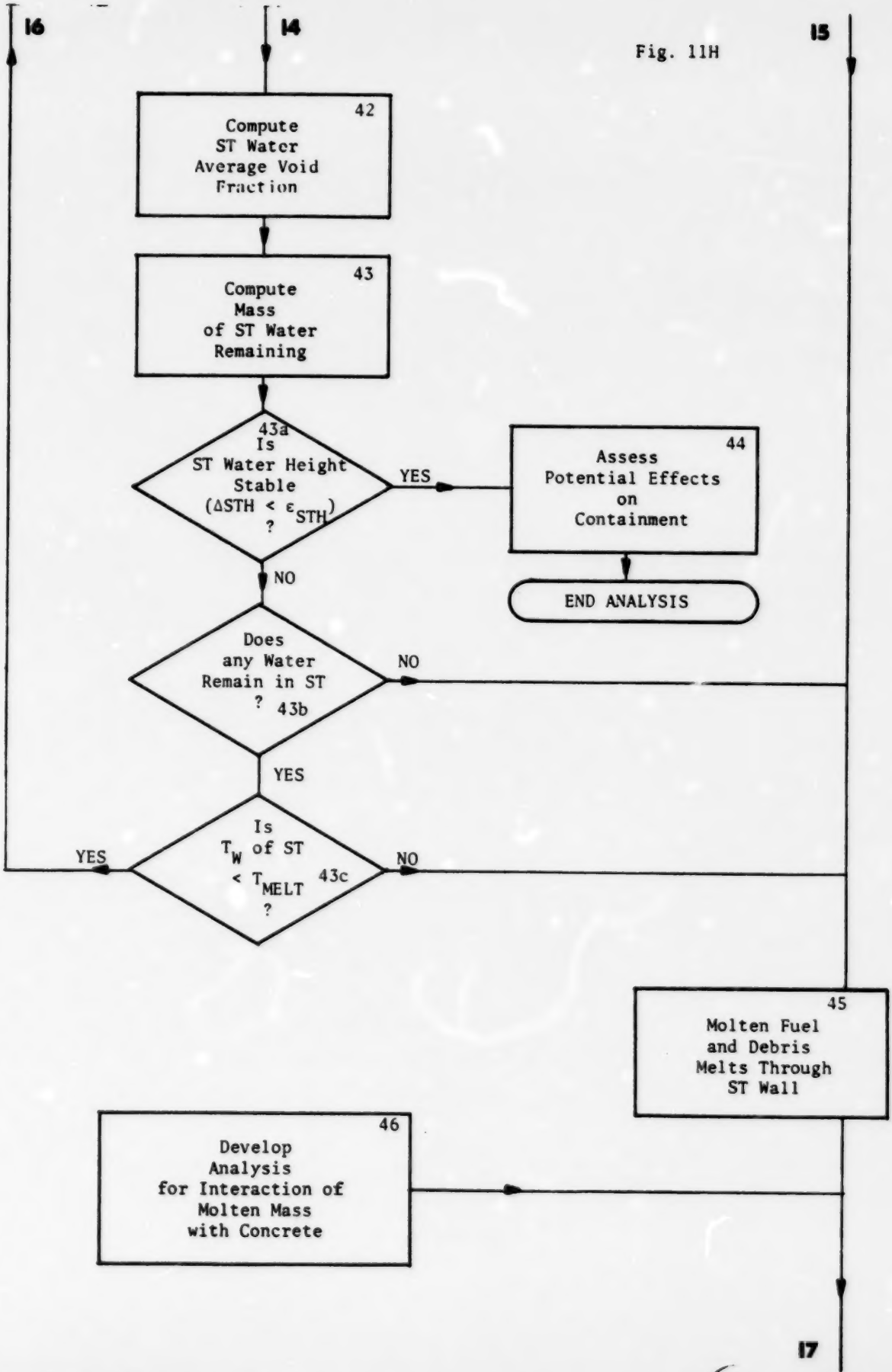

12
13
Fig. 11G
37a
Is ST Cooling Still Effective ?
NO
Accident Sequence not Considered
YES
38
Compute Temperature History of Molten Heat Source and Water in ST and ST WALL
Is Temp. of Water in ST < 100°C ? 38a
YES
Is T WALL of ST < T MELT ? 38b
YES
Is T WALL of ST Stable (ΔT W < ε STW) ? 38c
NO
NO
NO
YES
39
Assess Potential Effects on Containment
END ANALYSIS
Initialize Parameters
40
Develop Analysis for Boiling of ST Water
t=t+Δt Proceed to next time step
41
Compute ST Water Evaporation Rate
16
14
15

Fig. 11H


16
14
15
42
Compute ST Water Average Void Fraction
43
Compute Mass of ST Water Remaining
43a
Is ST Water Height Stable ($\Delta STH < \varepsilon_{STH}$) ?
YES
44
Assess Potential Effects on Containment
END ANALYSIS
NO
Does any Water Remain in ST ? 43b
NO
YES
Is T_W of ST $< T_{MELT}$? 43c
YES
NO
45
Molten Fuel and Debris Melts Through ST Wall
46
Develop Analysis for Interaction of Molten Mass with Concrete
17

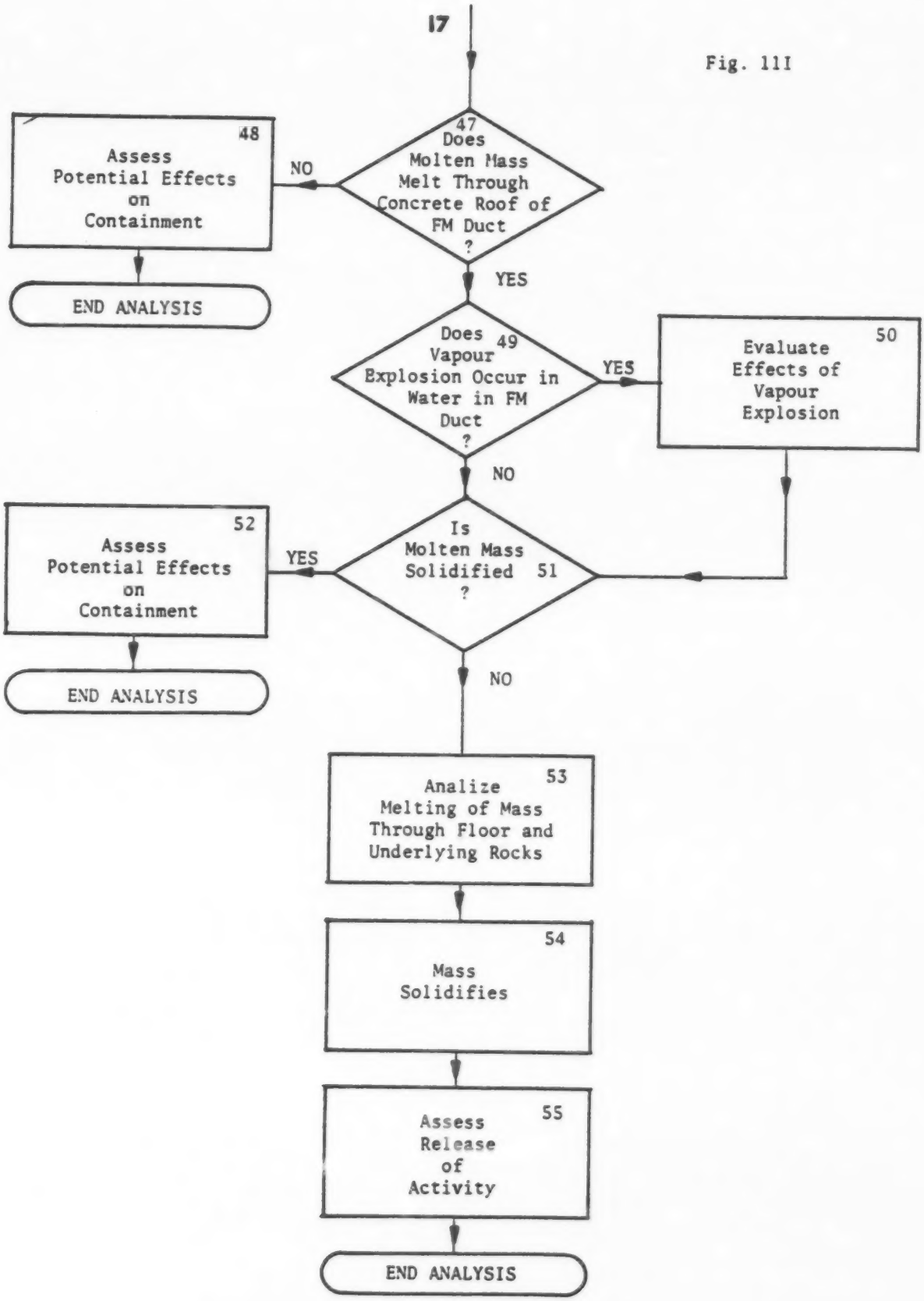

17
47
Does Molten Mass Melt Through Concrete Roof of FM Duct ?
NO
48
Assess Potential Effects on Containment
END ANALYSIS
YES
49
Does Vapour Explosion Occur in Water in FM Duct ?
YES
50
Evaluate Effects of Vapour Explosion
NO
Is Molten Mass Solidified ? 51
YES
52
Assess Potential Effects on Containment
END ANALYSIS
NO
53
Analize Melting of Mass Through Floor and Underlying Rocks
54
Mass Solidifies
55
Assess Release of Activity
END ANALYSIS

Fig. 11I

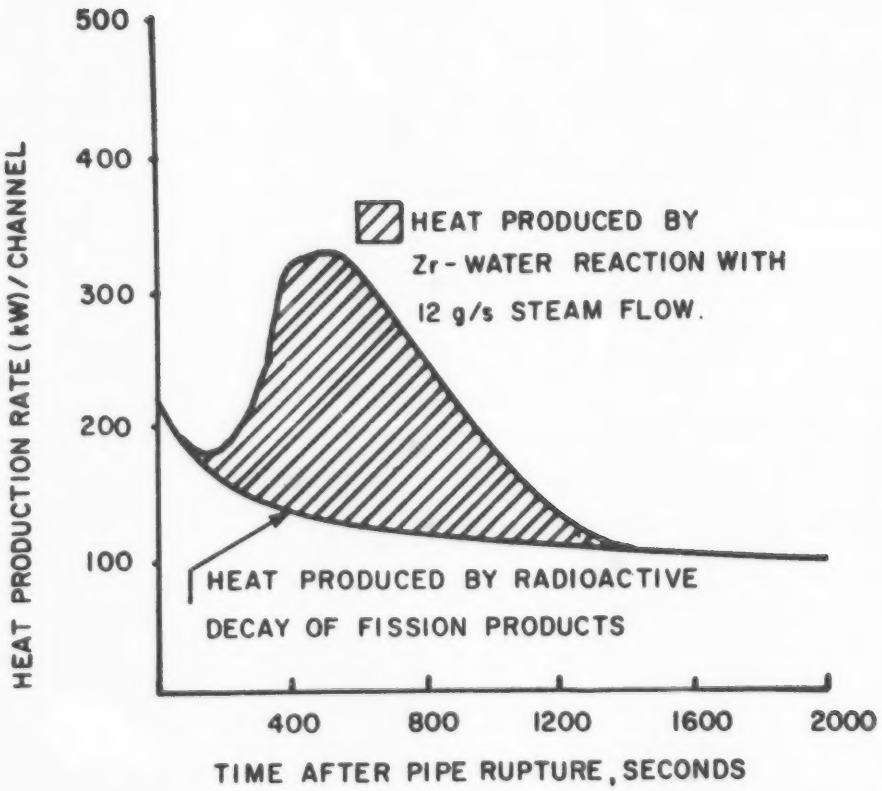


FIG. 12 HEAT PRODUCTION RATE BY ZIRCALOY-WATER REACTION. BRUCE MAXIMUM POWER CHANNEL CONDITIONS

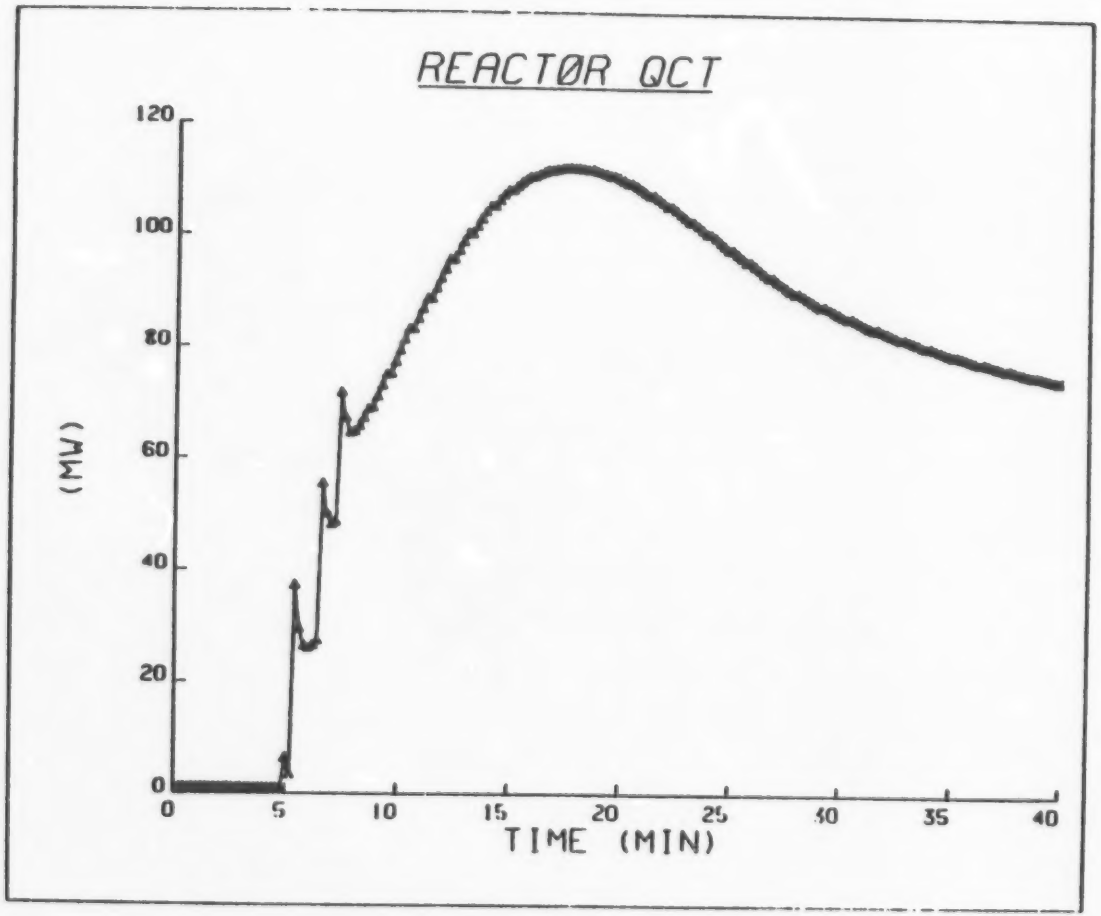


FIG. 13 HEAT SOURCE TO MODERATOR BRUCE REACTOR

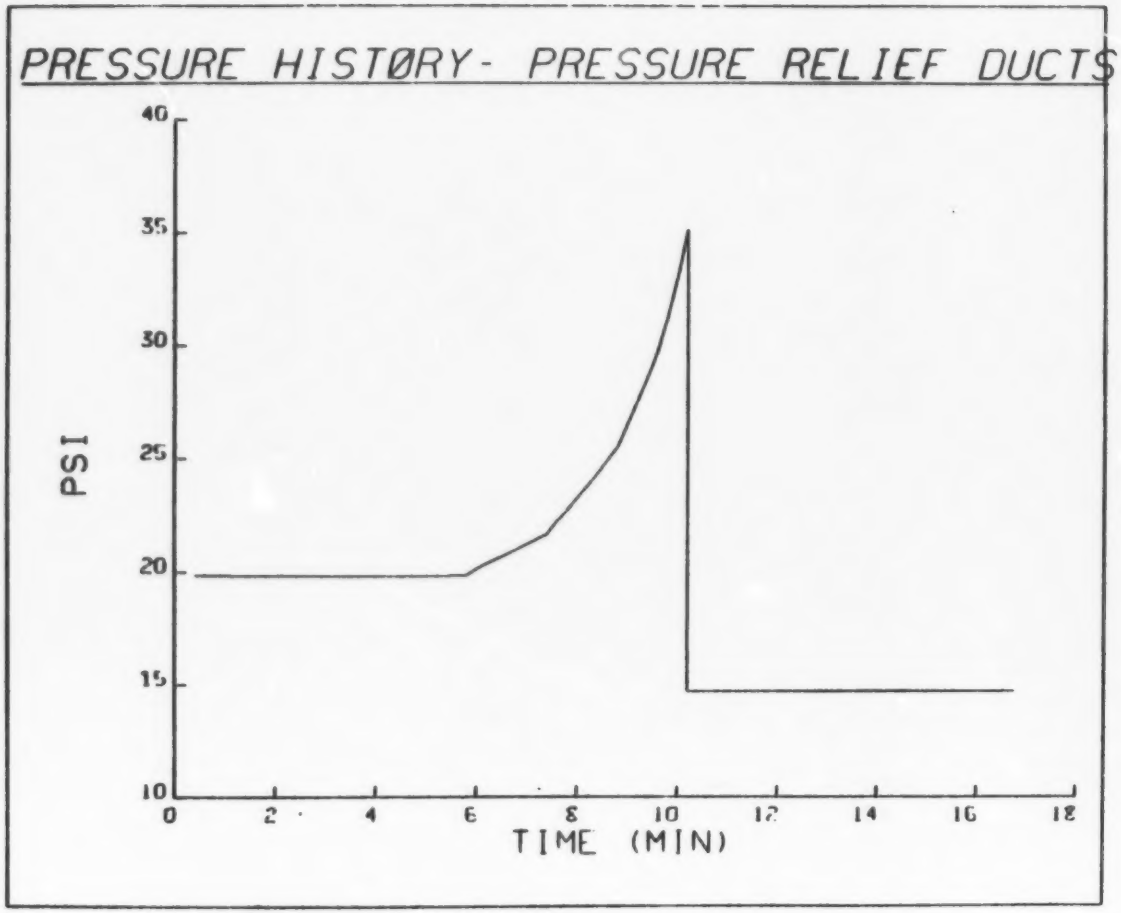


FIG. 14 PRESSURE IN CALANDRIA ACCIDENT SEQUENCE S11.

Acknowledgements

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The author thanks T.C. Currie for his significant help in developing the modified version of the IMPECC computer program used in the transient dry-patch analysis and the IMPECC-UCZ version of IMPECC. He also thanks J.A. Atkinson for his important contribution to the development of the program MODERATOR.

Thanks are extended to P. Cyr for preparing the figures and to Mrs. R. Thomas for typing the report.

The author acknowledges the helpful comments of F.R. Campbell and his colleagues on the AECB staff on the accident sequence analysis.

POOR

QUALITY

ORIGINAL